The Emergence and Impact of Intelligent Machines

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Lincoln Lab, MIT
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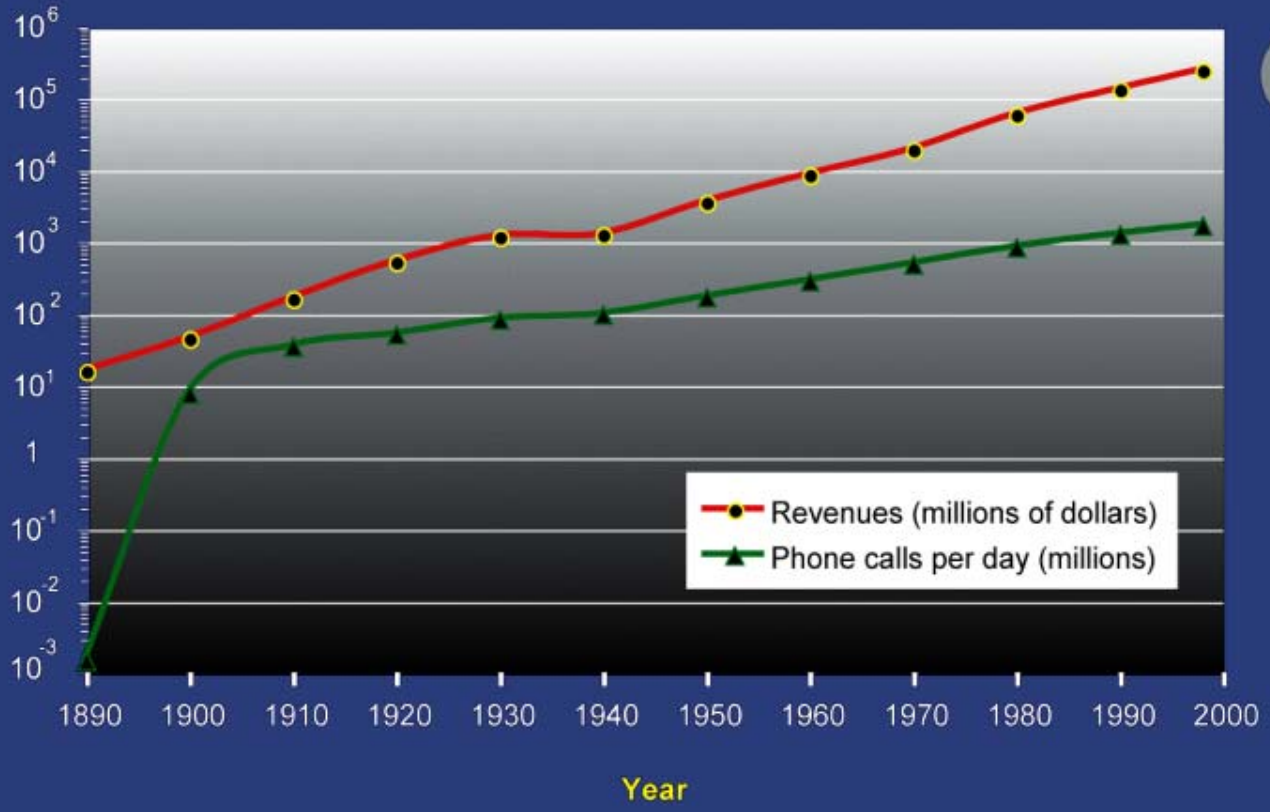
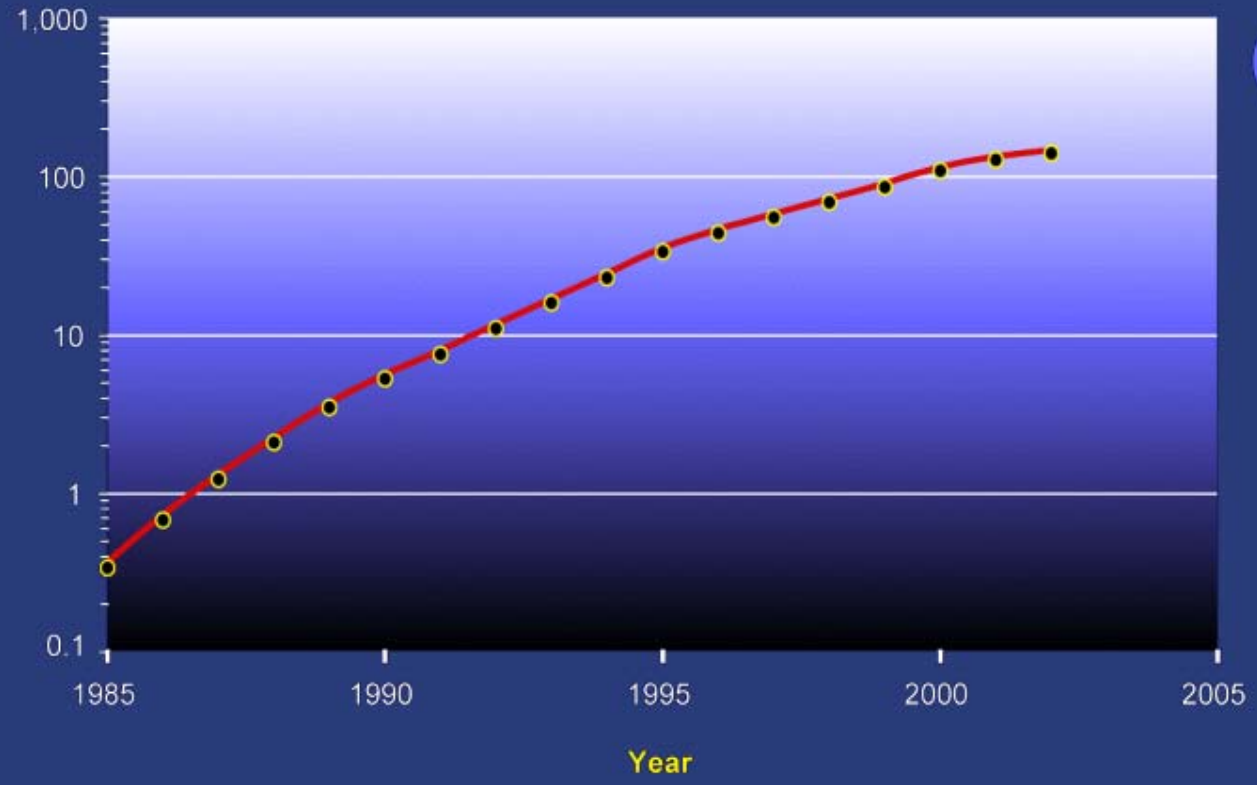
Growth of U.S. Phone Industry



Logarithmic Plot

Source: AT&T Labs

Estimated U.S. Cell Phone Subscribers

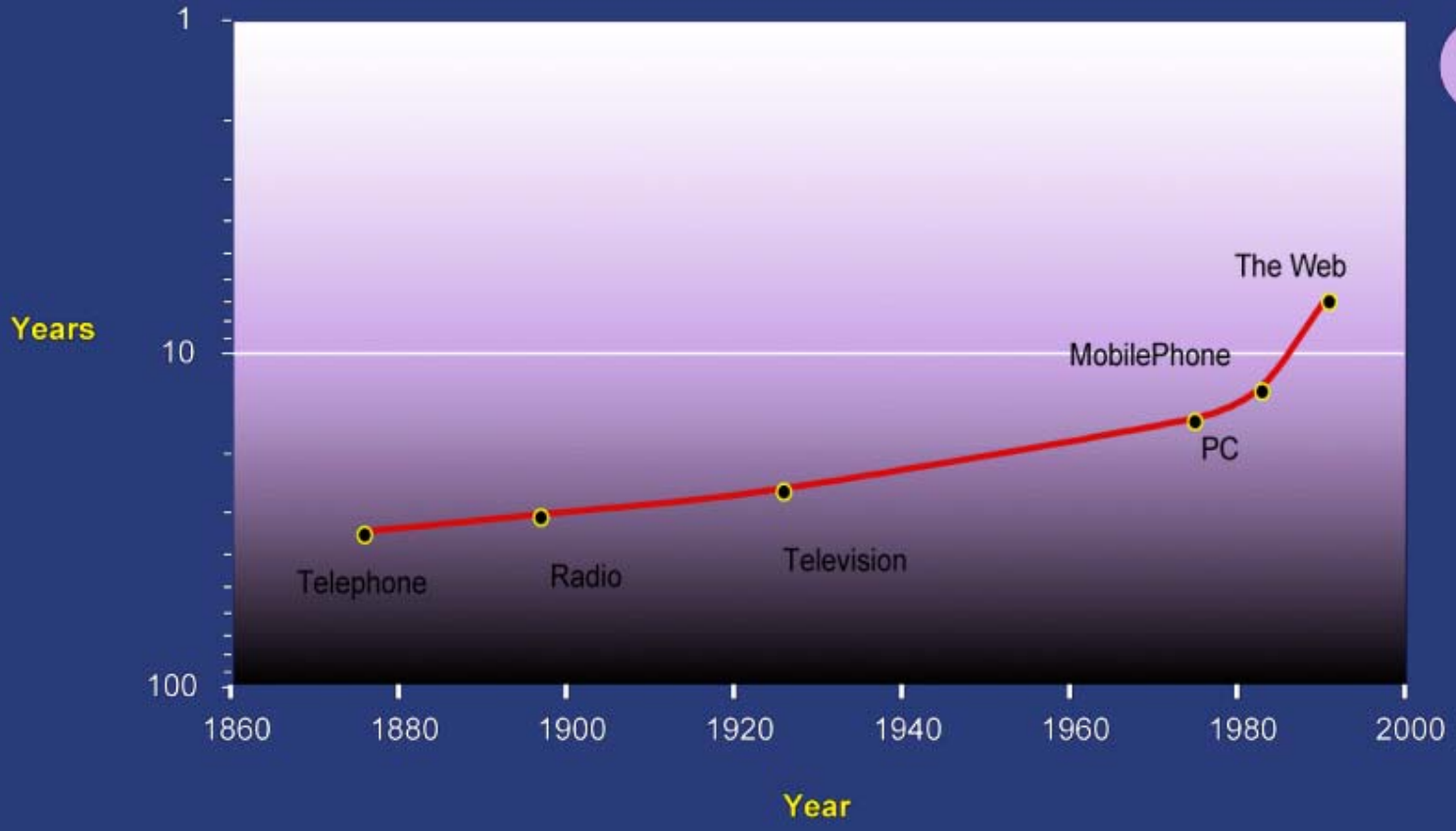


Logarithmic Plot

Source: Cellular Telecommunications & Internet Association

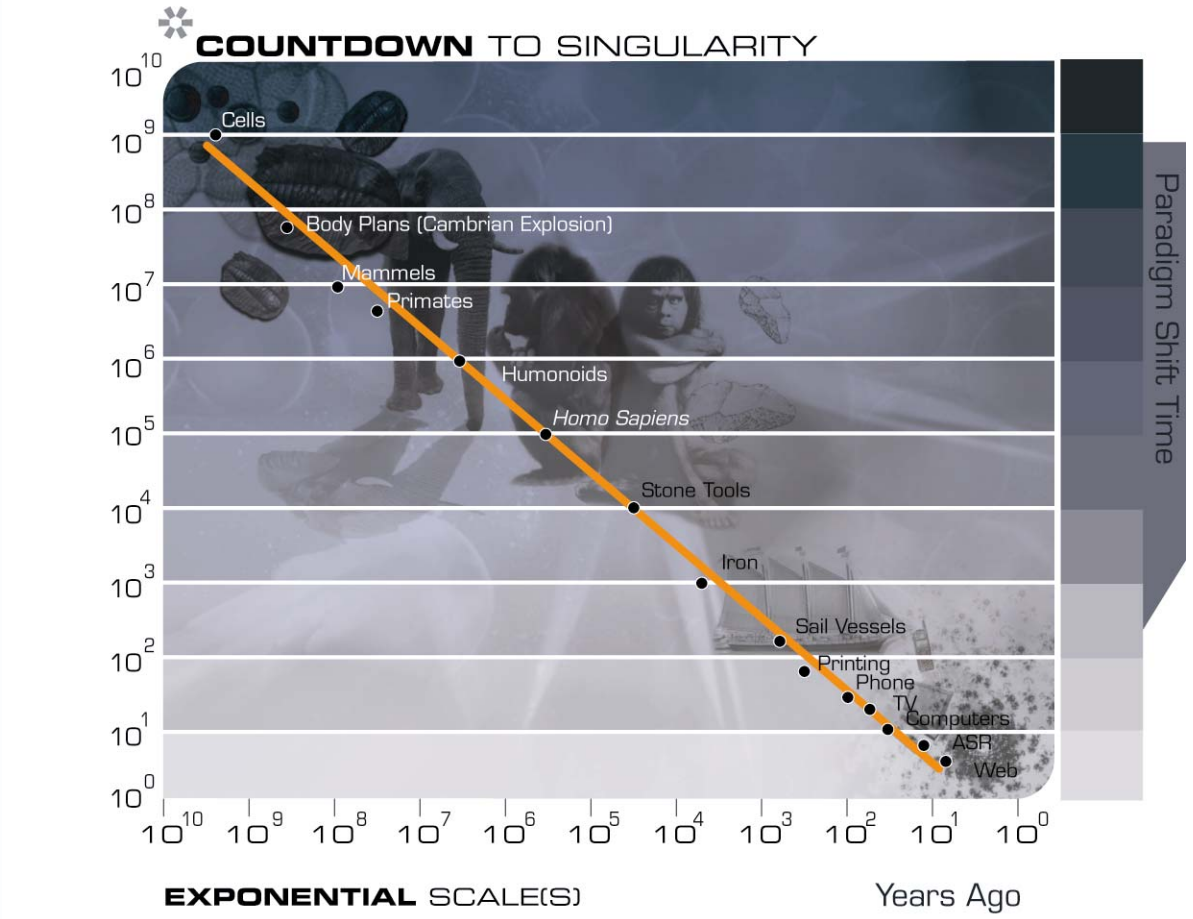
Mass Use of Inventions

Years Until Use by 1/4 U.S. Population



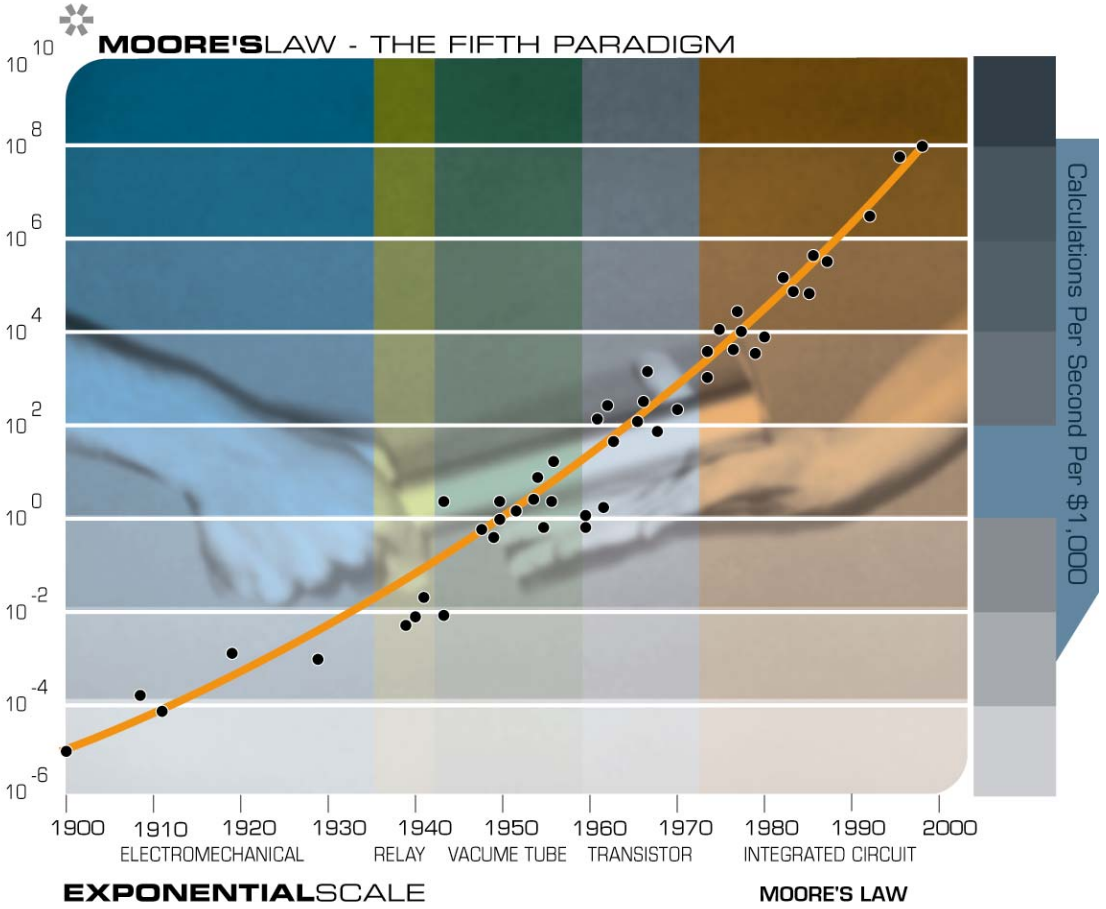
Logarithmic Plot

Source: The Millennium Notebook, Newsweek

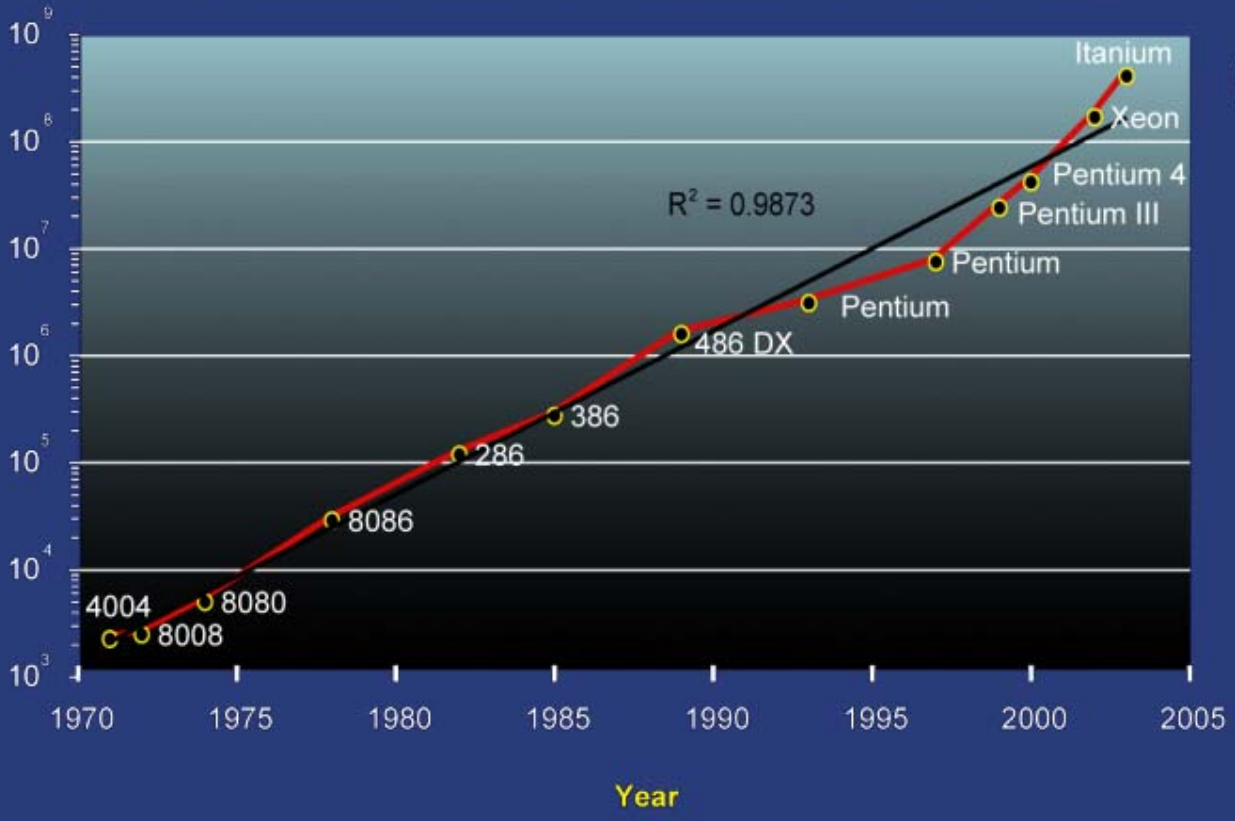

COUNTDOWN TO SINGULARITY
Cells
Body Plans (Cambrian Explosion)
Mammels
Primates
Humonoids
Homo Sapiens
Stone Tools
Iron
Sail Vessels
Printing
Phone
TV
Computers
ASR
Web
Paradigm Shift Time
EXPONENTIAL SCALE(S)
Years Ago

Measure	IBM 7094	Notebook Circa 2003
Year	**1967**	**2003**
Processor Speed (MIPS)	**0.25**	**1,000**
Main Memory (K Bytes)	**144**	**256,000**
Approximate Cost (2003 $)	**$2,000,000**	**$2,000**

22 Doublings of Price-Performance in 36 years, doubling time: 19 months
not including vastly greater RAM memory, disk storage, instruction set, etc.


MOORE'SLAW - THE FIFTH PARADIGM
10 10
10 8
10 6
10 4
10 2
10 0
10 -2
10 -4
10 -6
Calculations Per Second Per $1,000
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000
ELECTROMECHANICAL
RELAY
VACUME TUBE
TRANSISTOR
INTEGRATED CIRCUIT
EXPONENTIALSCALE
MOORE'S LAW

Transistors (Intel processors)

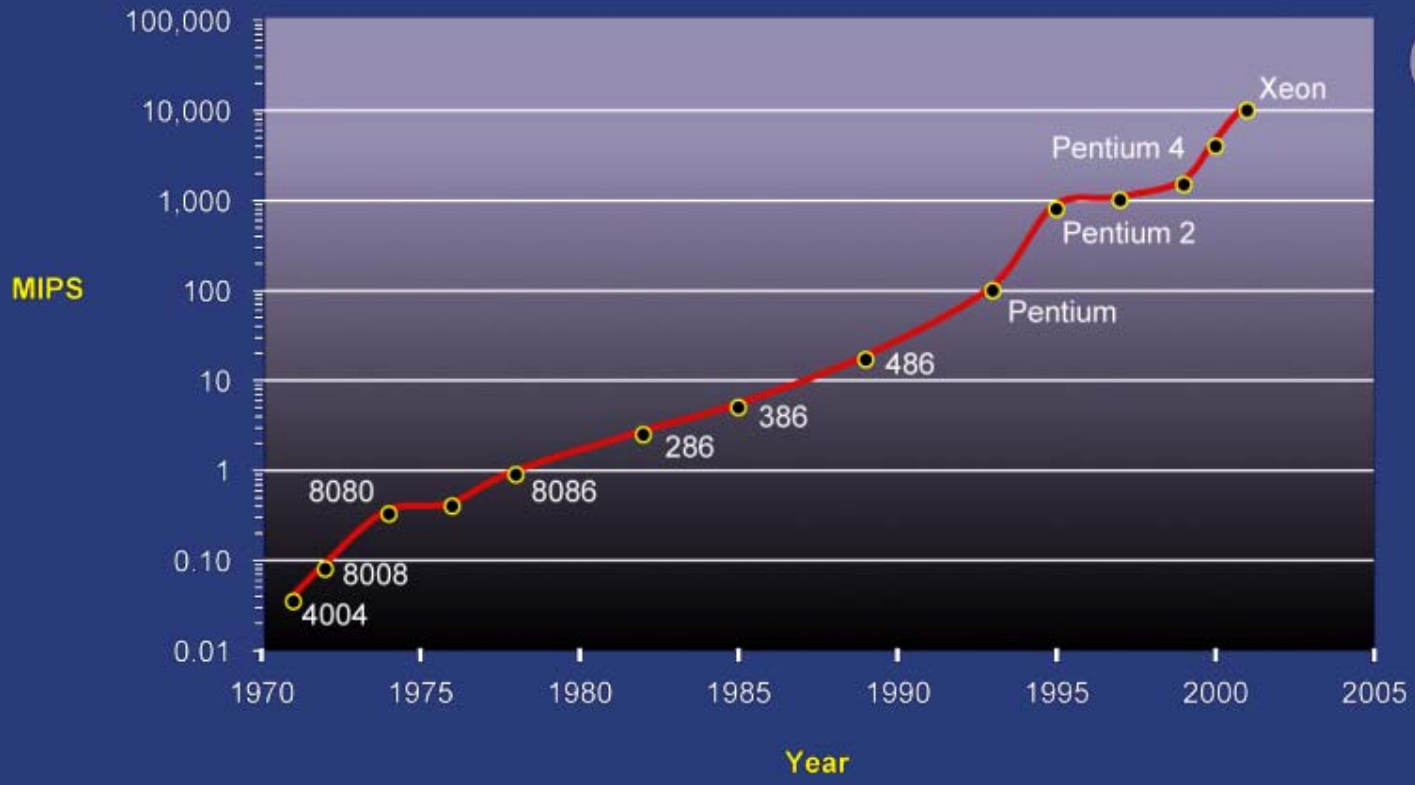


Logarithmic Plot

Source: Intel Research

Doubling time: 2 years

Processor Performance (MIPS)



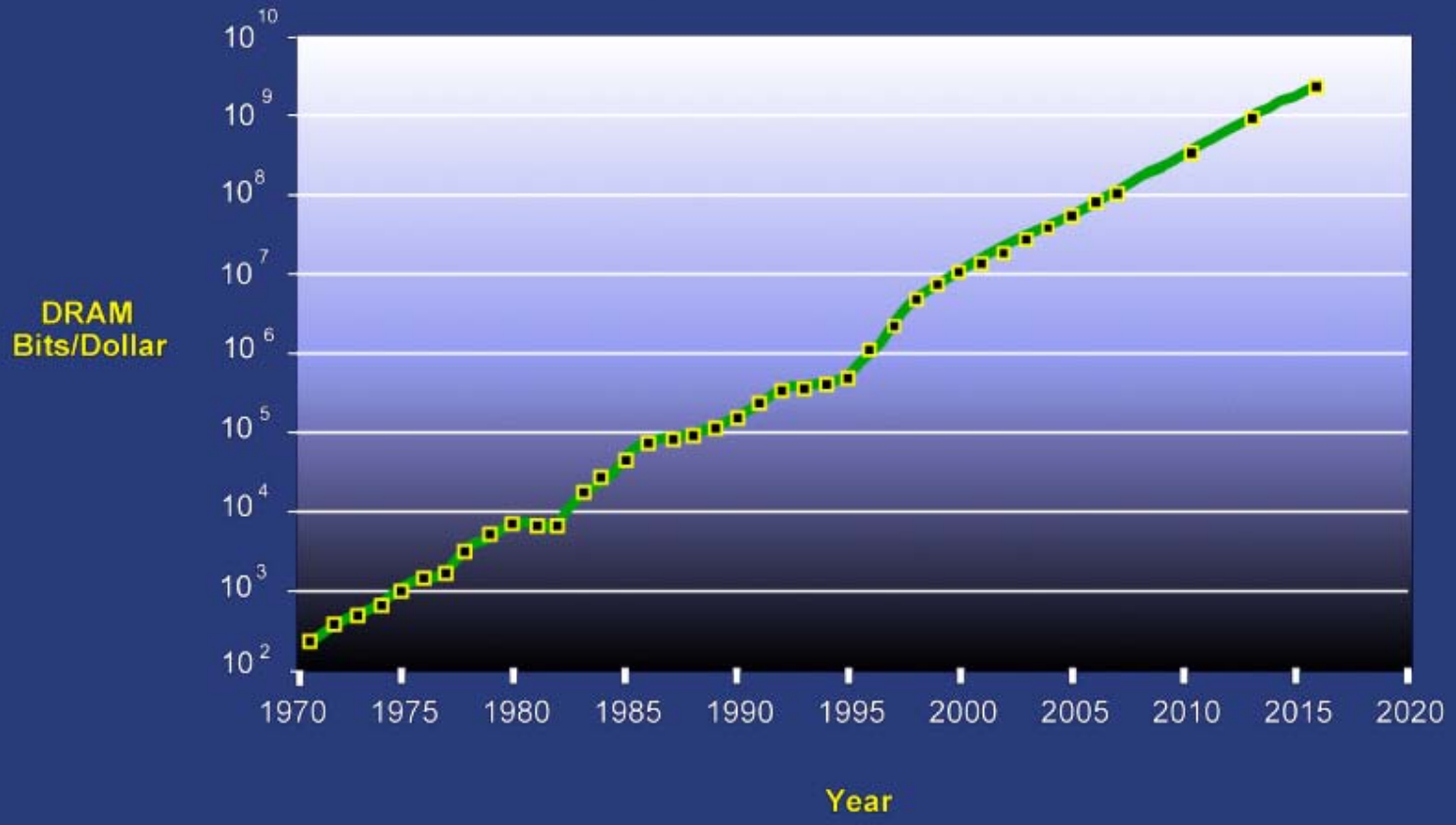
Logarithmic Plot

Source: Intel

Doubling time: 1.8 years

Dynamic RAM Memory

Bits per Dollar at Production

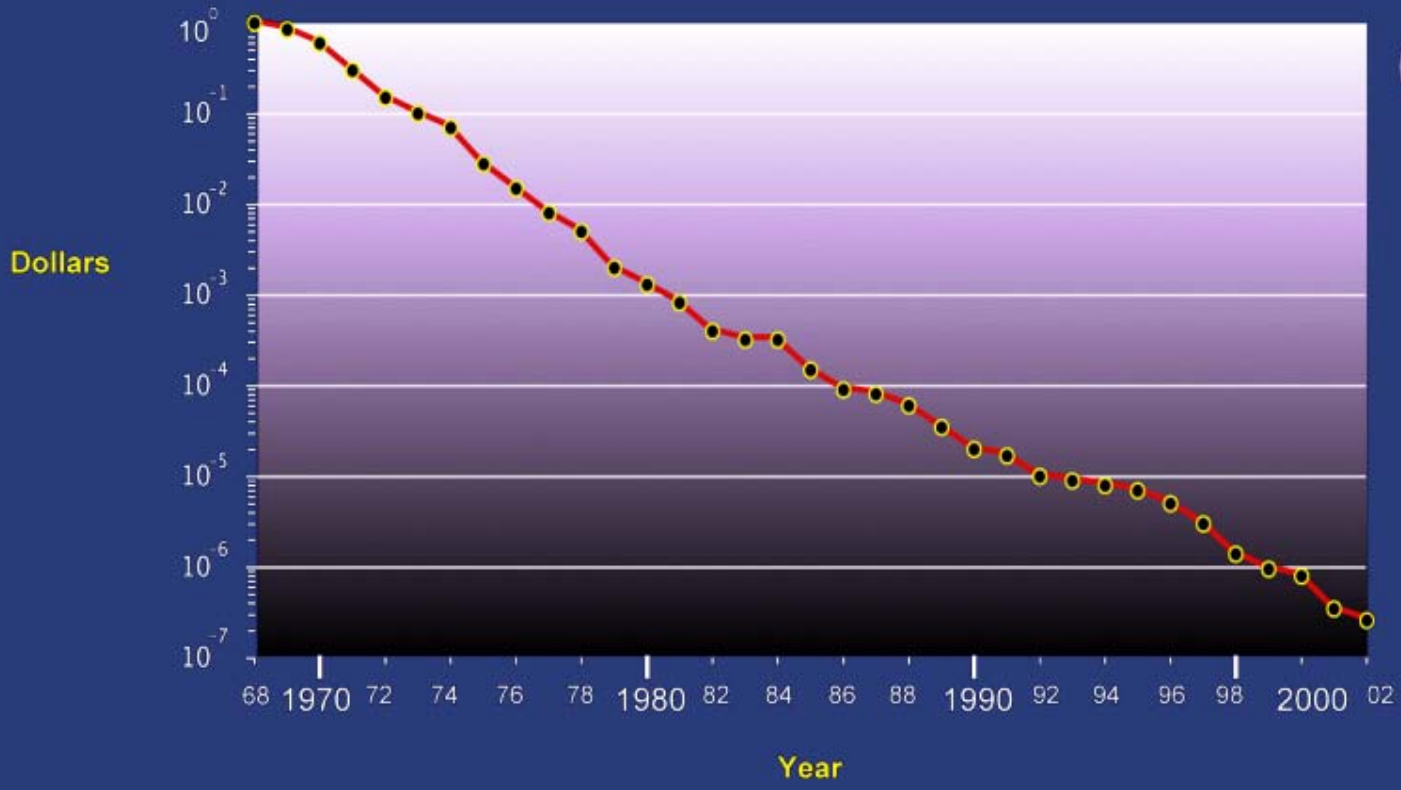


Logarithmic Plot

Source: SEMATECH ITRS Roadmap

Doubling time: 1.5 years

Average Transistor Price

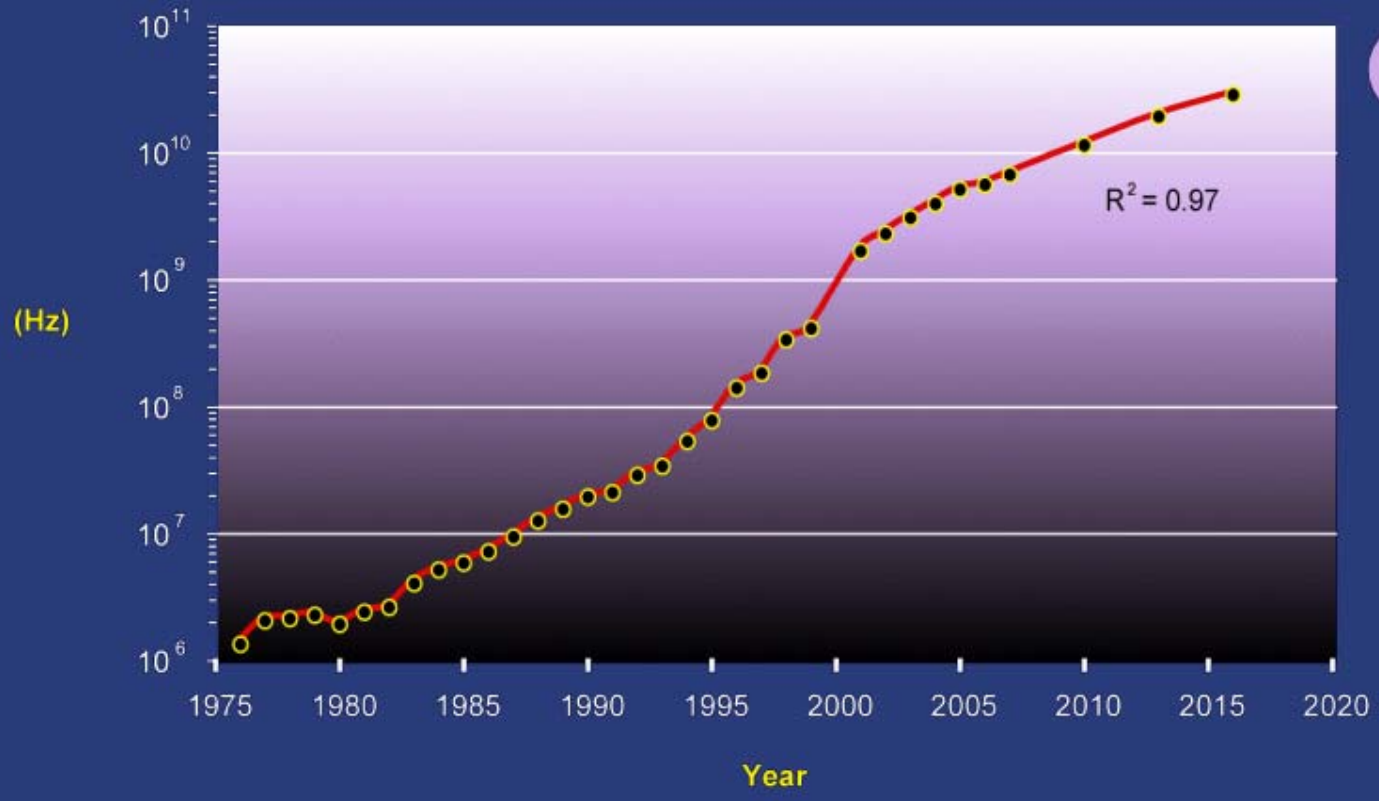


Logarithmic Plot

Source: Dataquest/Intel

Halving time: 1.6 years

Microprocessor Clock Speed

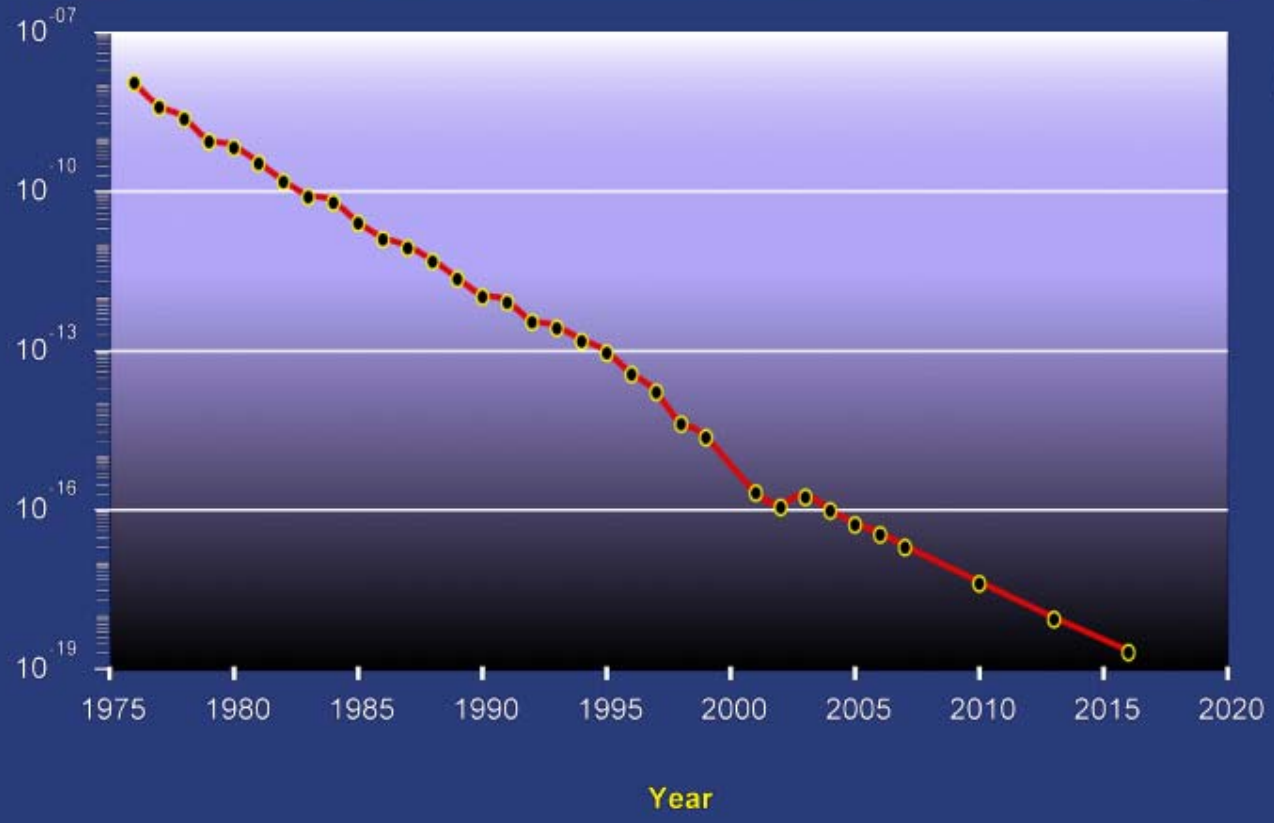


Logarithmic Plot

Sources: Berndt et al., ITRS

Doubling time: 2.7 years

Microprocessor Cost Per Transistor Cycle

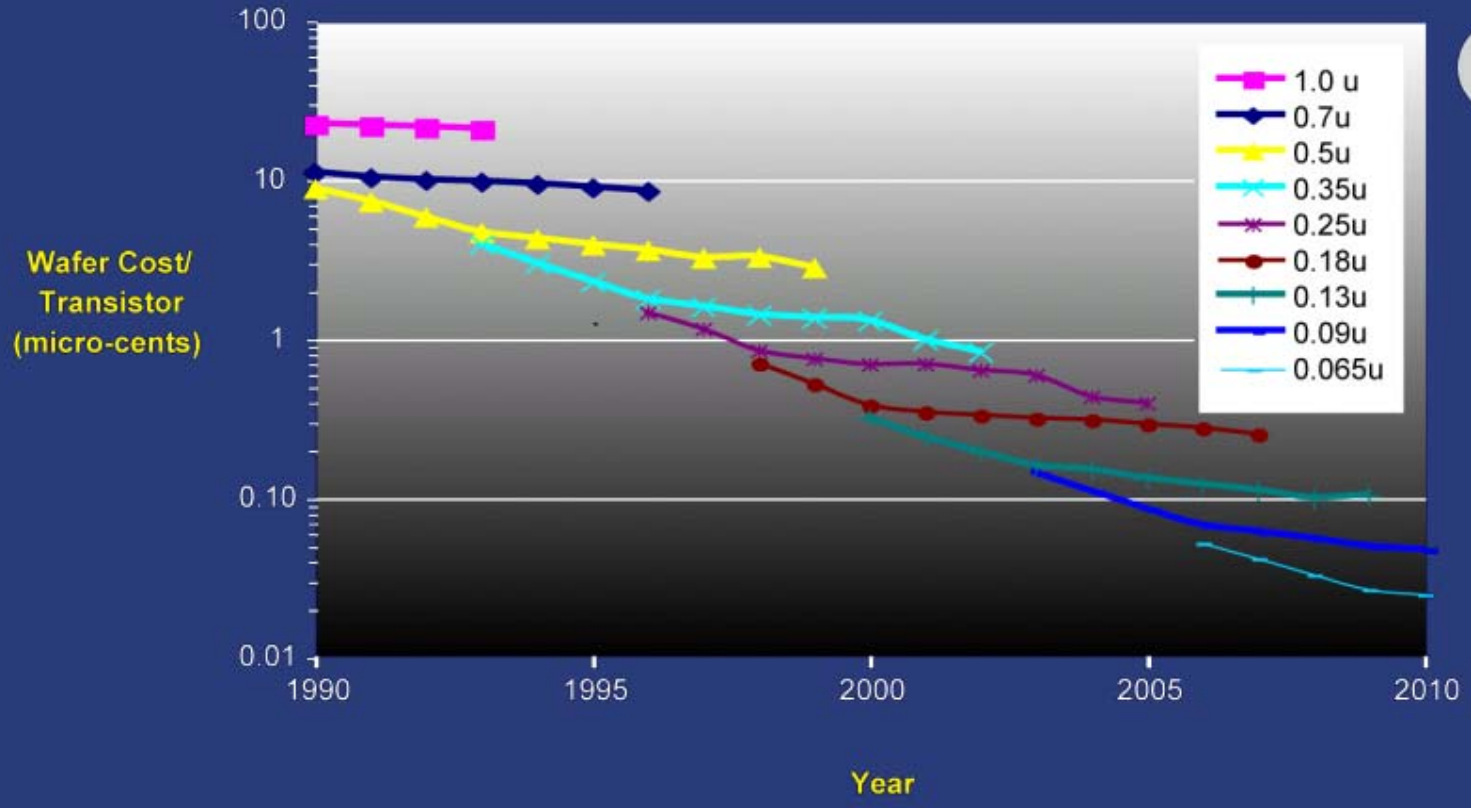


Logarithmic Plot

Sources: Berndt et al., SEMATECH ITRS Roadmap

Halving time: 1.1 years

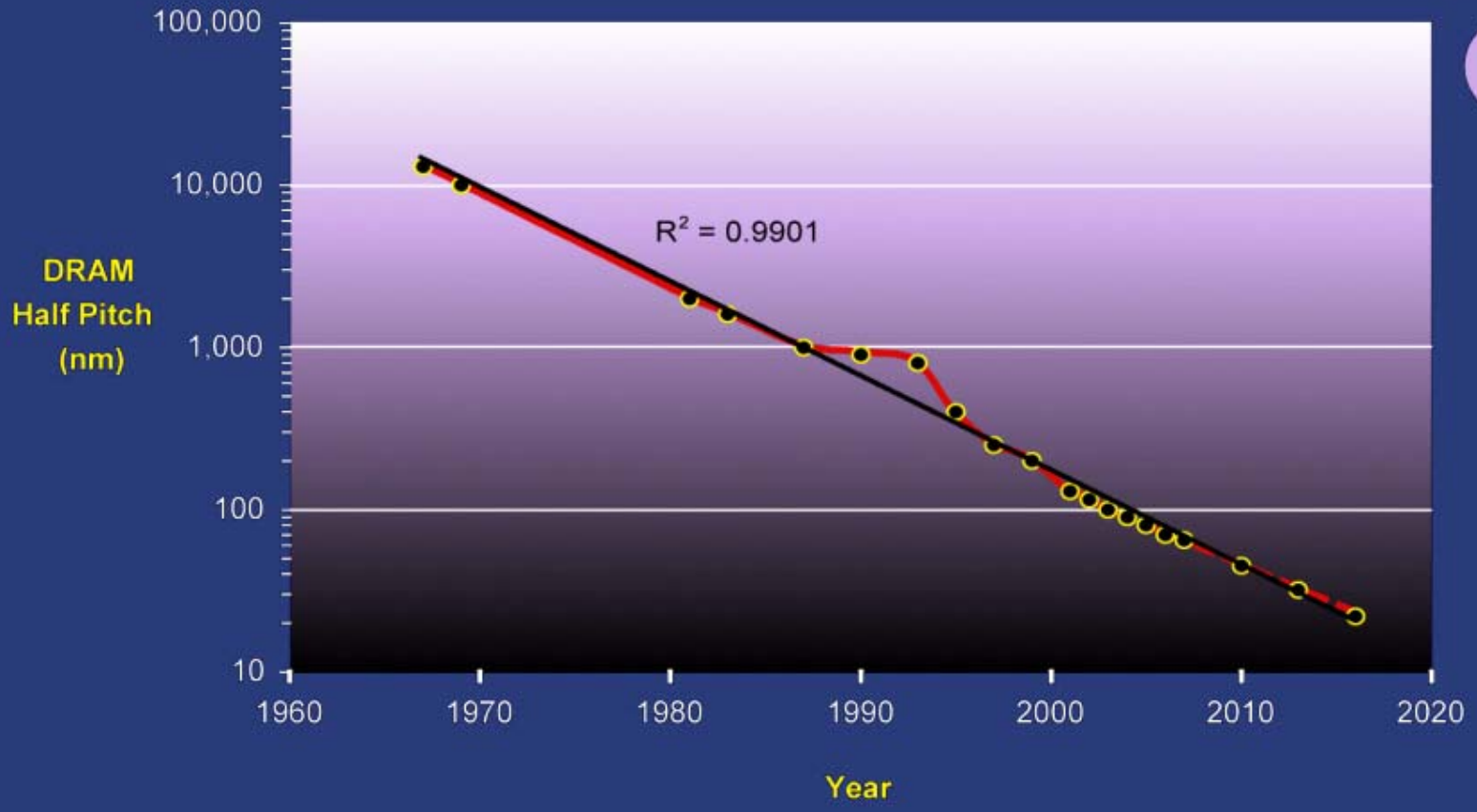
Transistor Manufacturing Costs Falling



Logarithmic Plot

Source: SEMATECH ITRS Roadmap

Dynamic RAM Memory "Half Pitch" Feature Size

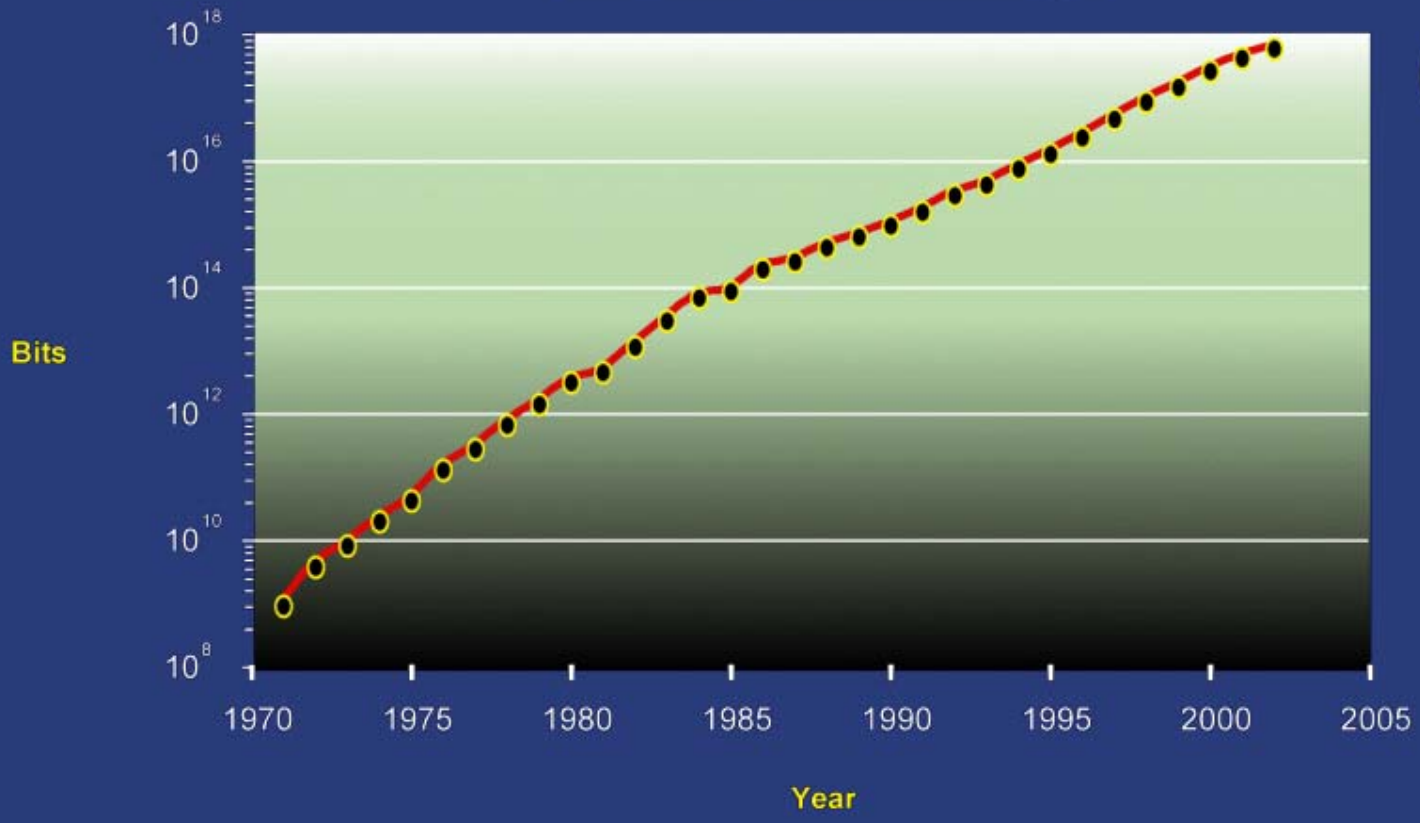


Logarithmic Plot

Source: Intel,SEMATECH ITRS Roadmap

Halving time: 5.4 years

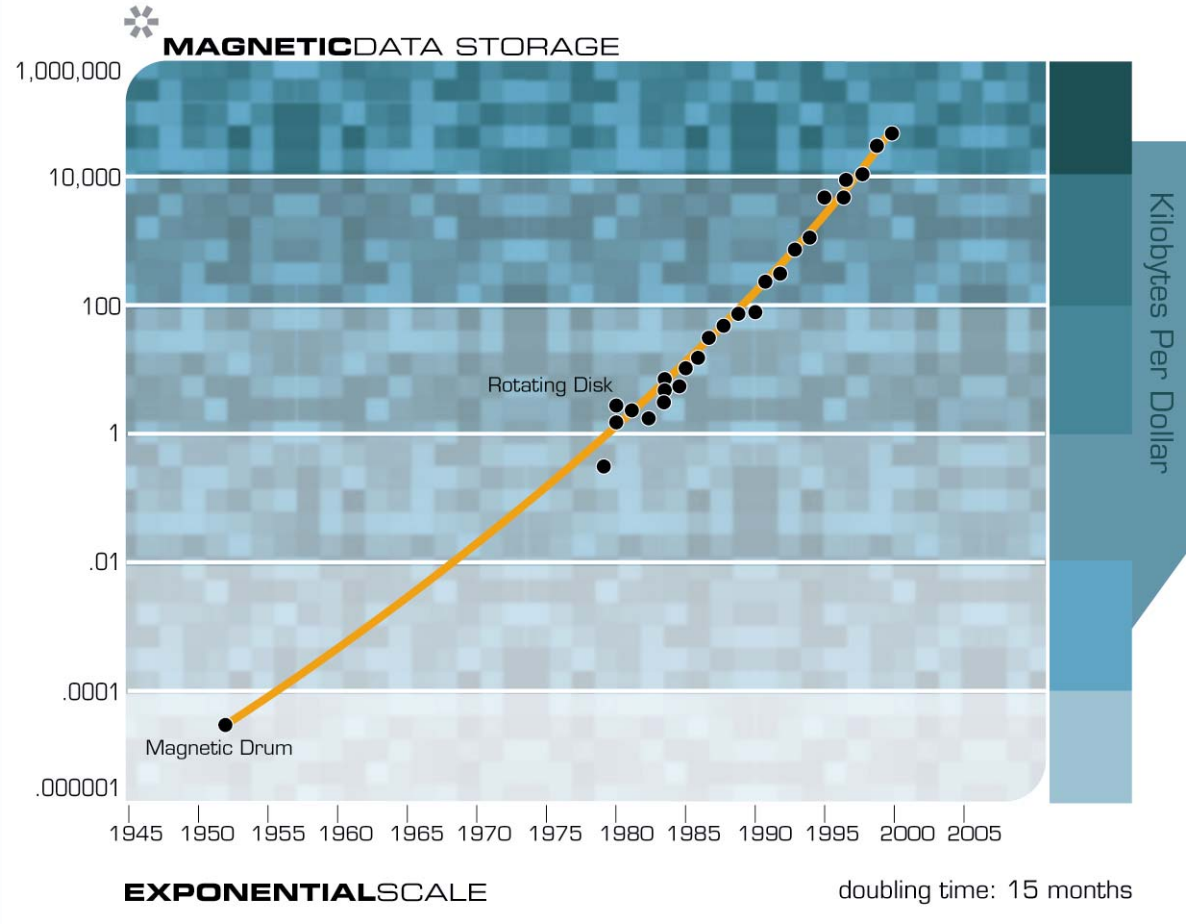
Total Bits Shipped

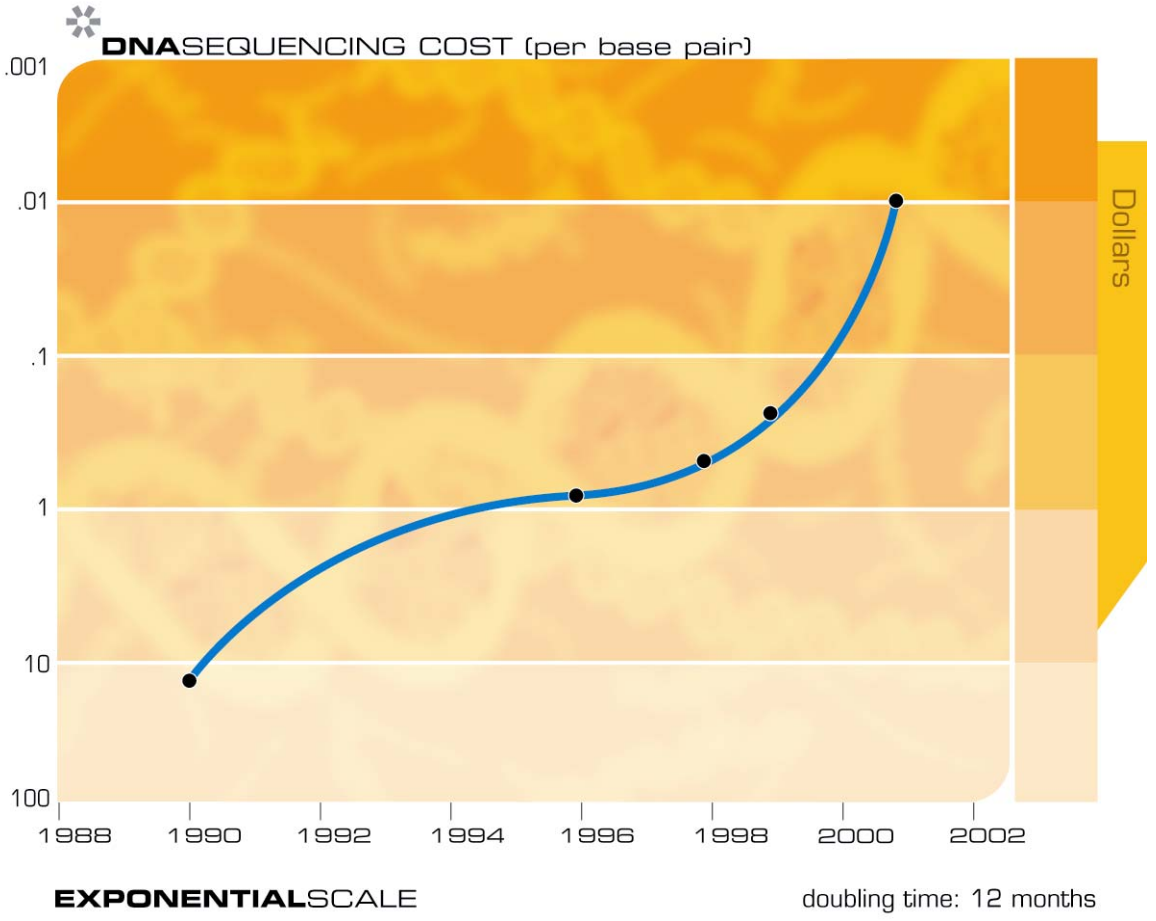


Logarithmic Plot

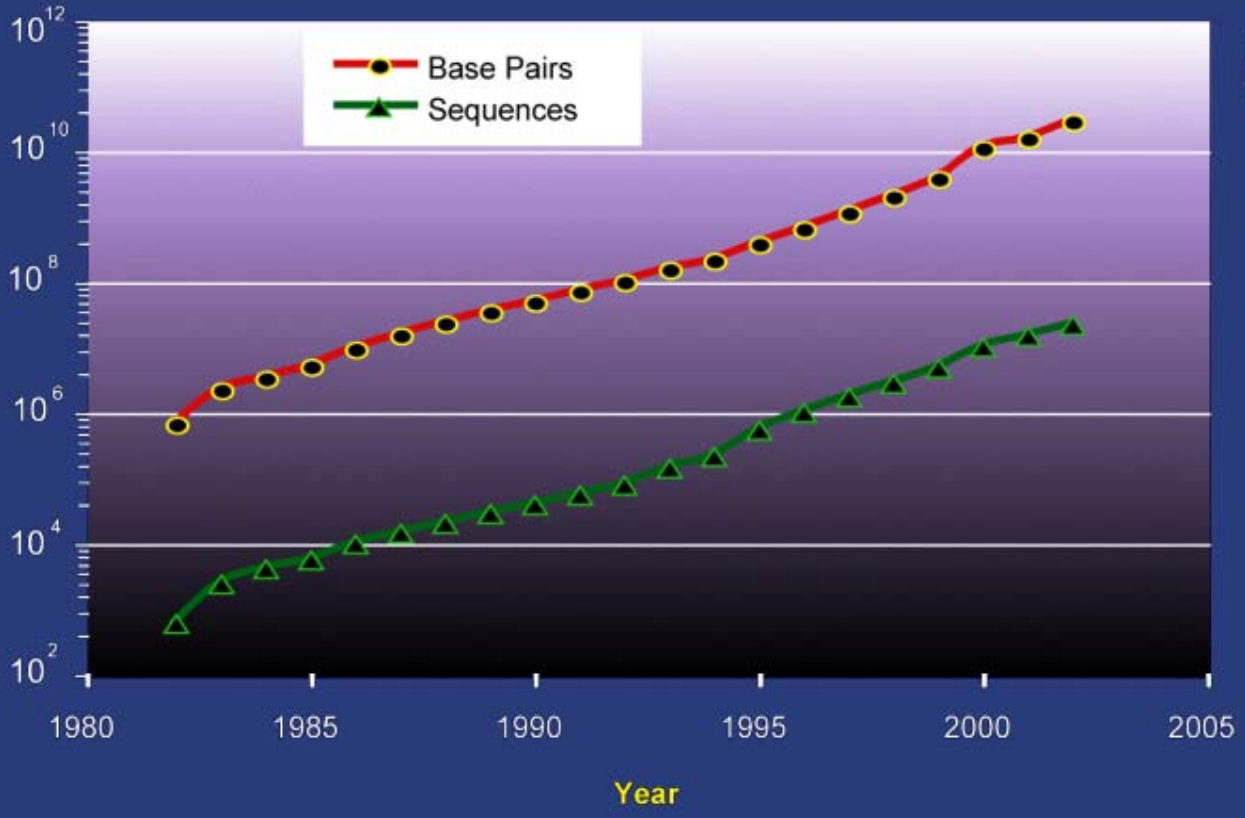
Source: In-Stat/MDR

Doubling time: 1.1 years


MAGNETICDATA STORAGE
1,000,000
10,000
100
1
.01
.0001
.000001
Rotating Disk
Magnetic Drum
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005
Kilobytes Per Dollar
EXPONENTIALSCALE
doubling time: 15 months

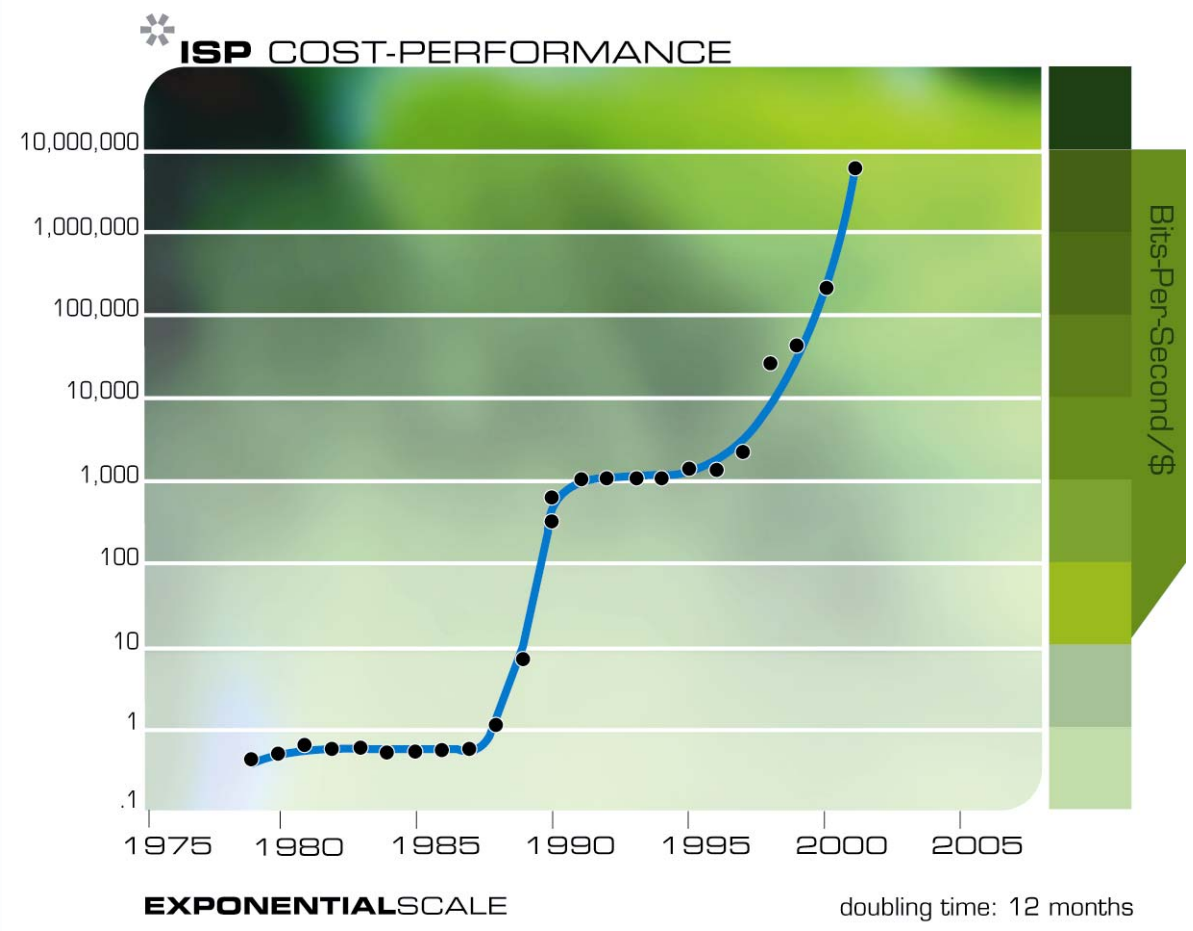

DNASEQUENCING COST (per base pair)
.001
.01
.1
1
10
100
Dollars
1988
1990
1992
1994
1996
1998
2000
2002
EXPONENTIALSCALE
doubling time: 12 months

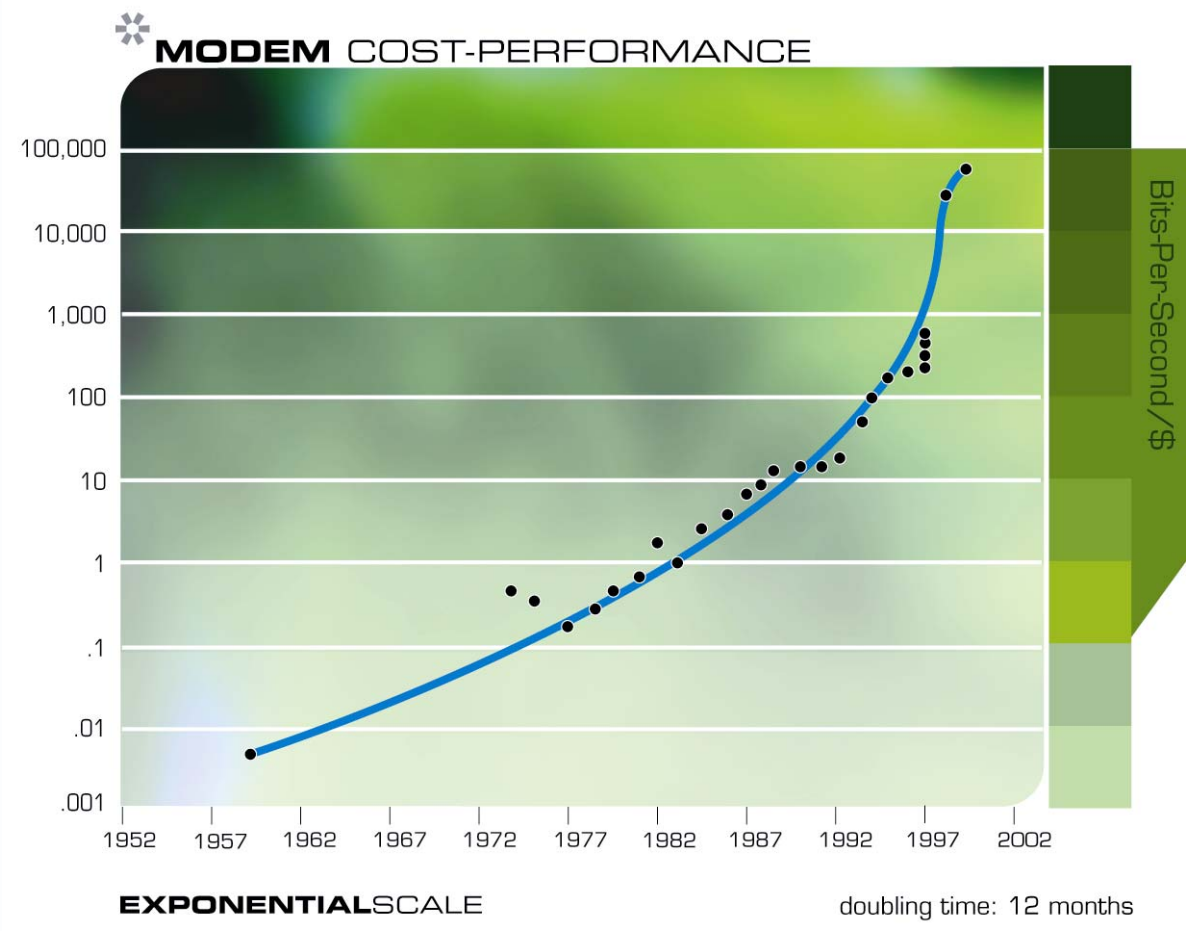
Growth in Genbank DNA Sequence Data

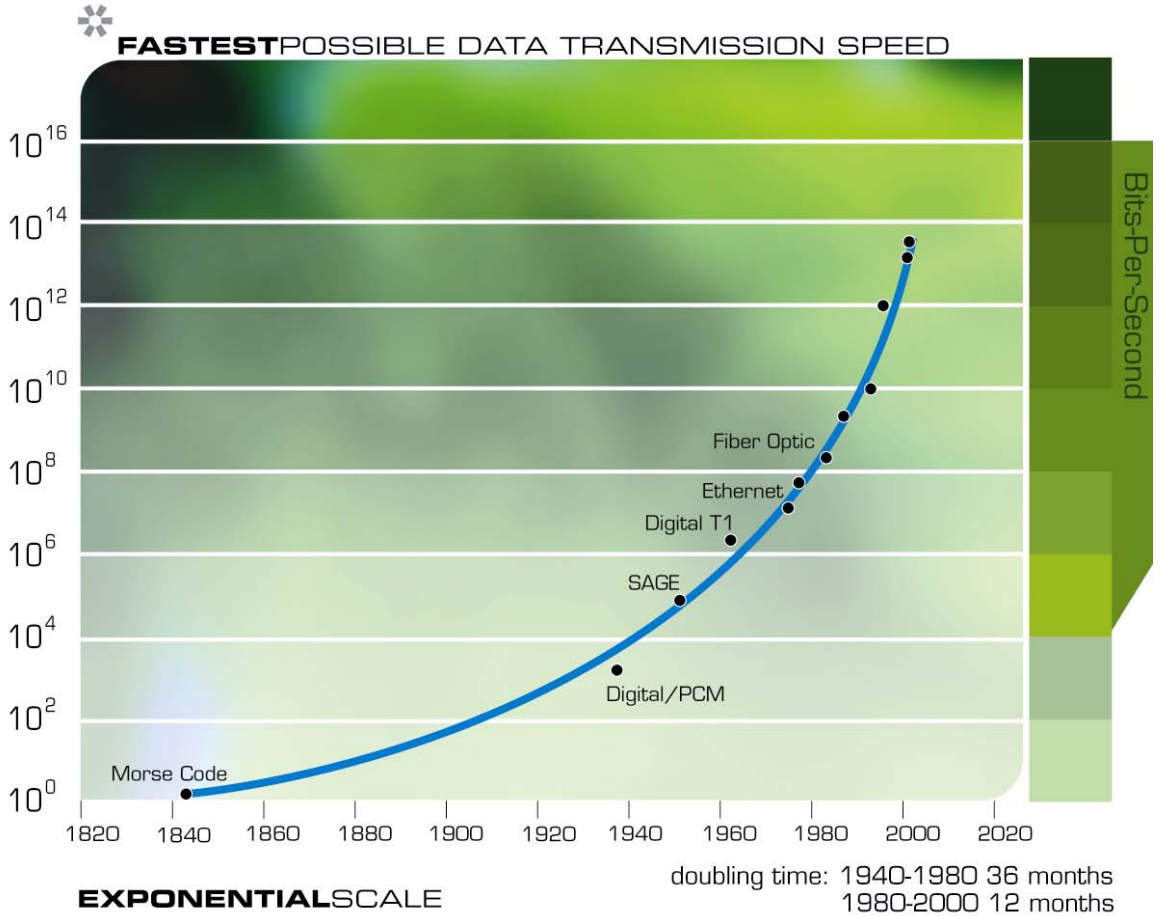


Logarithmic Plot

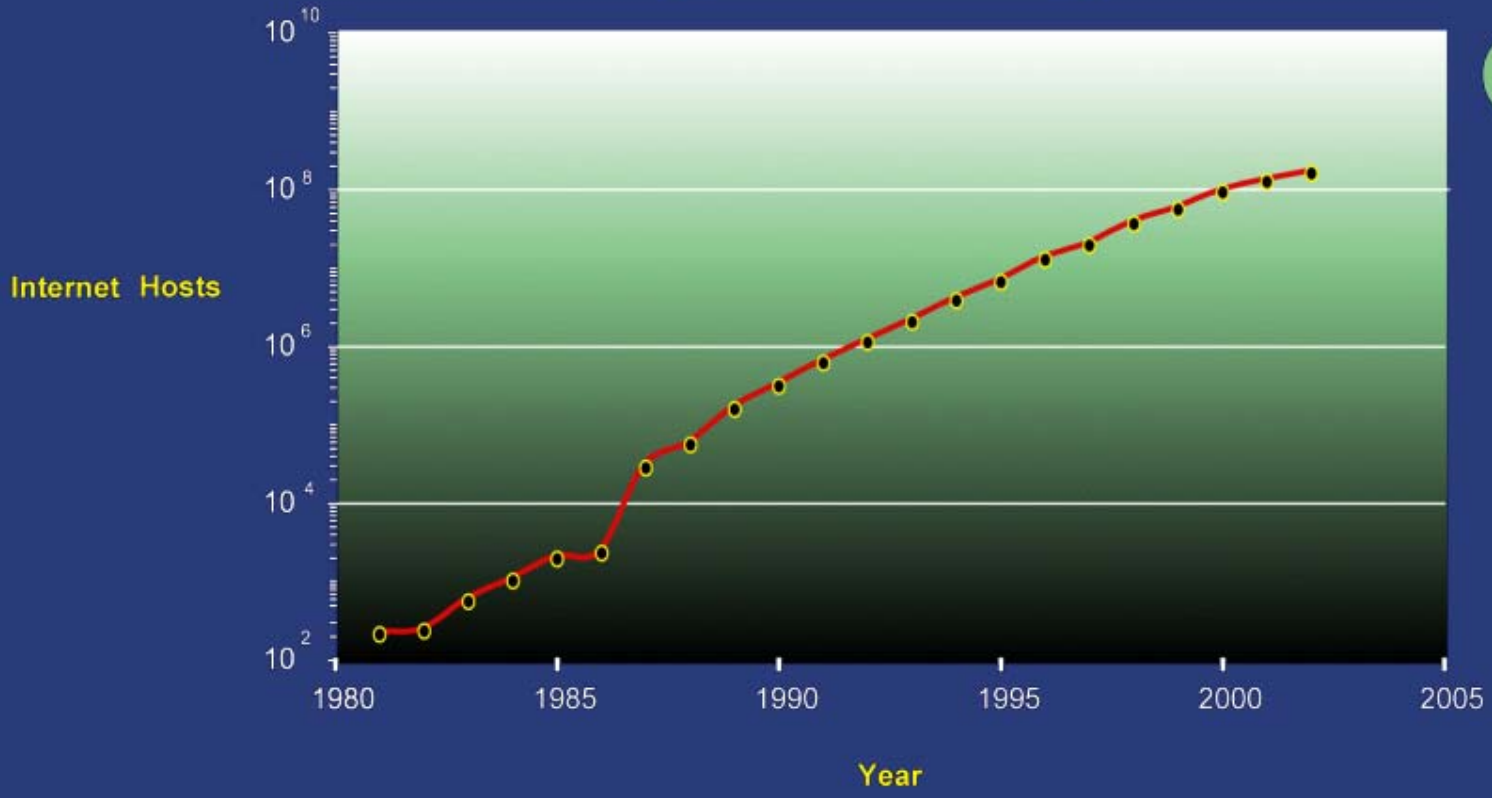
Source: GenBank


ISP COST-PERFORMANCE
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
.1
1975
1980
1985
1990
1995
2000
2005
Bits-Per-Second/$
EXPONENTIALSCALE
doubling time: 12 months


MODEM COST-PERFORMANCE
100,000
10,000
1,000
100
10
1
.1
.01
.001
1952
1957
1962
1967
1972
1977
1982
1987
1992
1997
2002
Bits-Per-Second/$
EXPONENTIALSCALE
doubling time: 12 months


FASTESTPOSSIBLE DATA TRANSMISSION SPEED
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
Bits-Per-Second
Fiber Optic
Ethernet
Digital T1
SAGE
Digital/PCM
Morse Code
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
EXPONENTIALSCALE
doubling time: 1940-1980 36 months
1980-2000 12 months

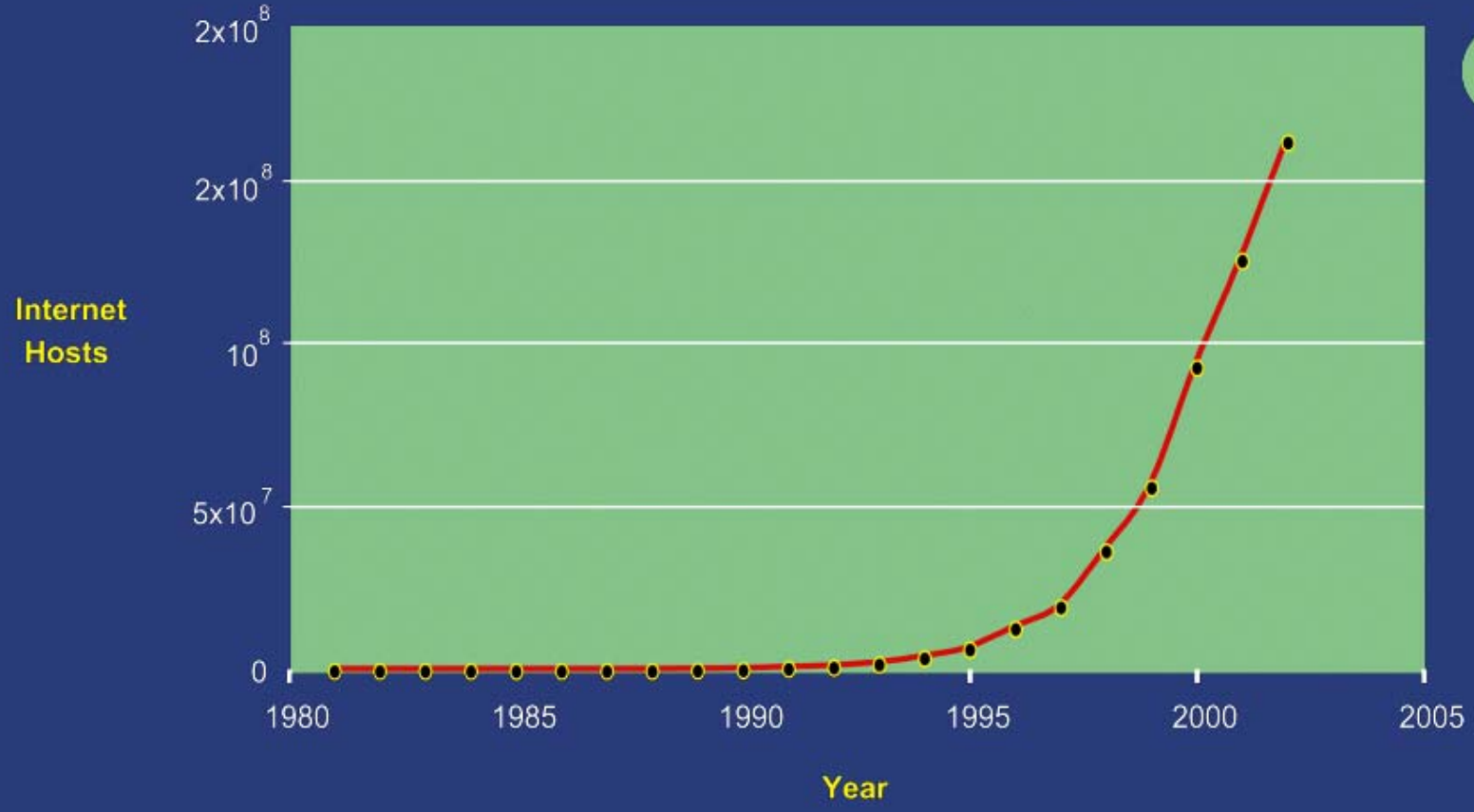
Internet Hosts



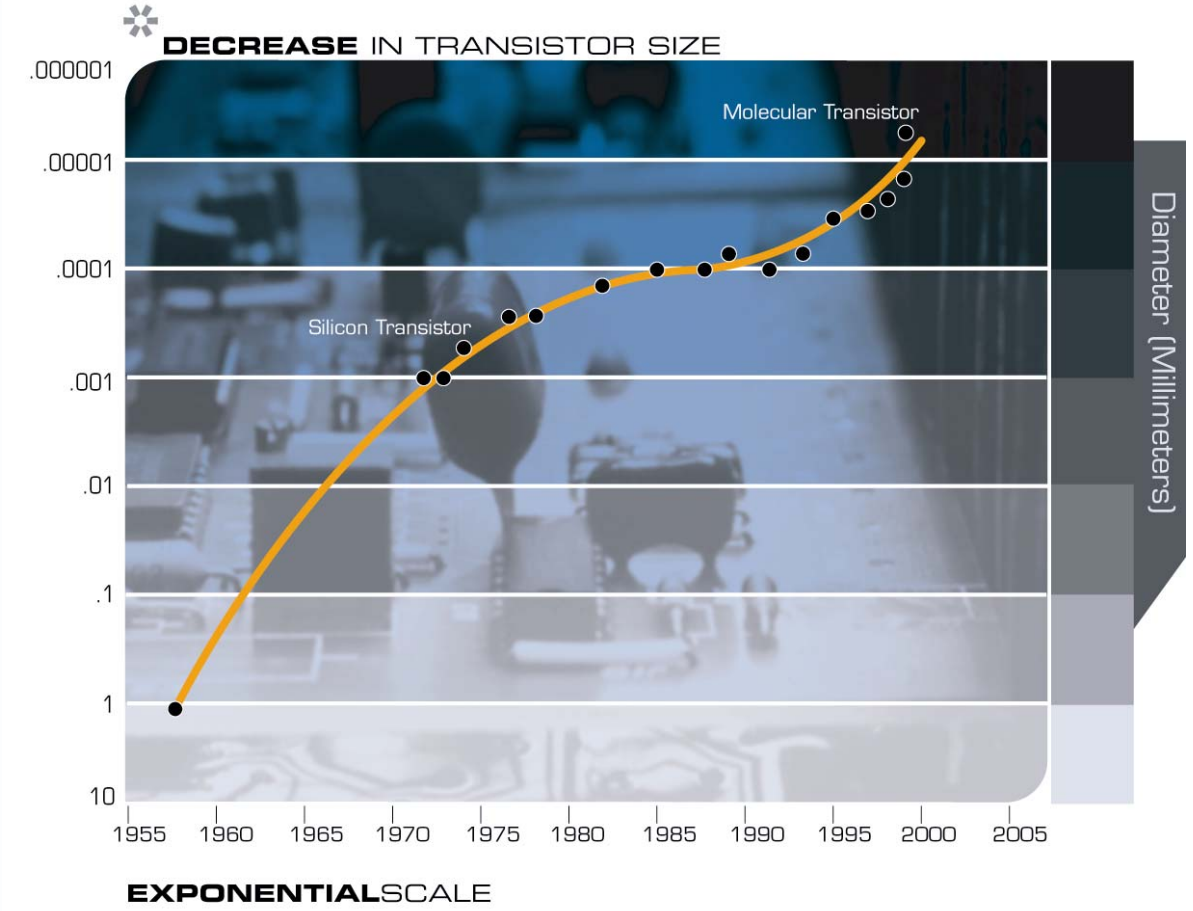
Logarithmic Plot

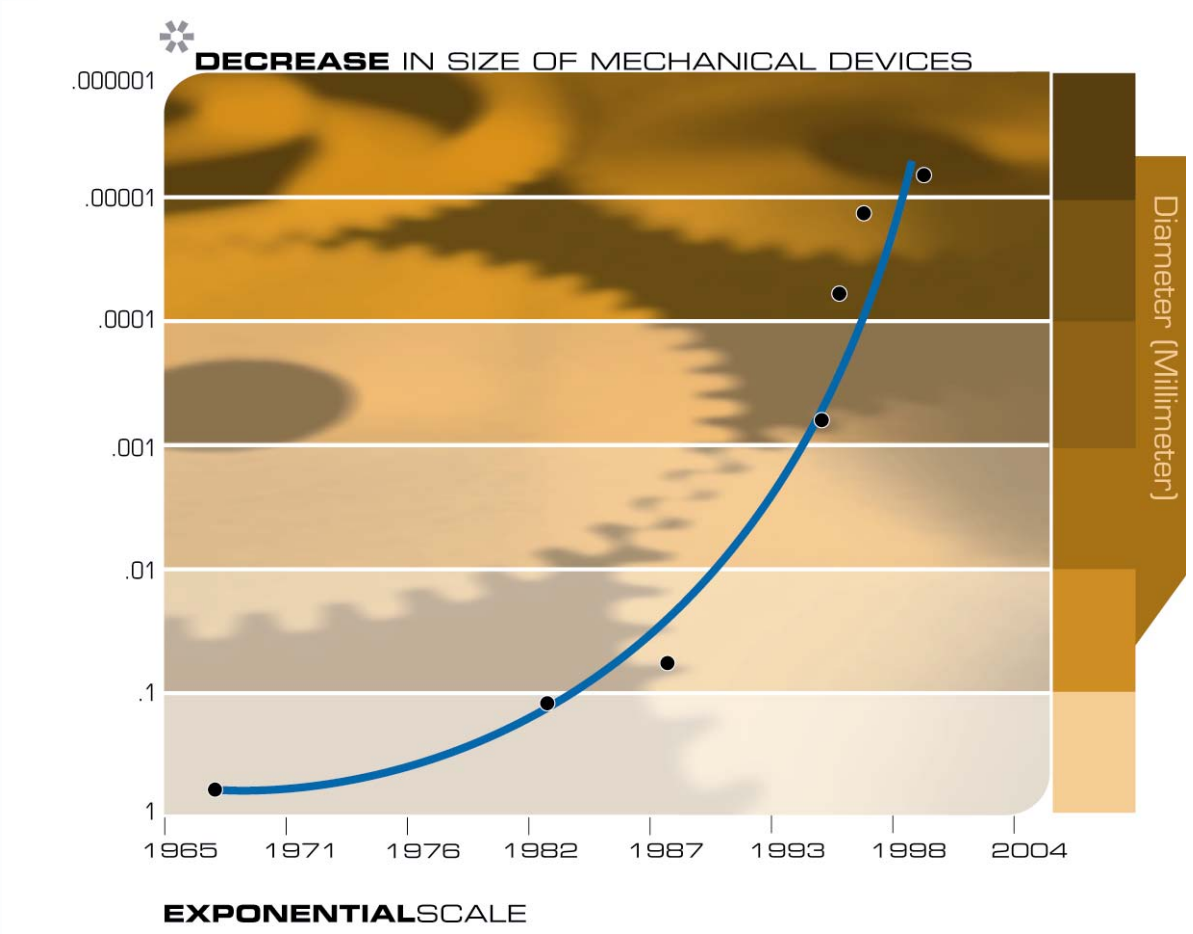
Source: Internet Software Consortium

Internet Hosts

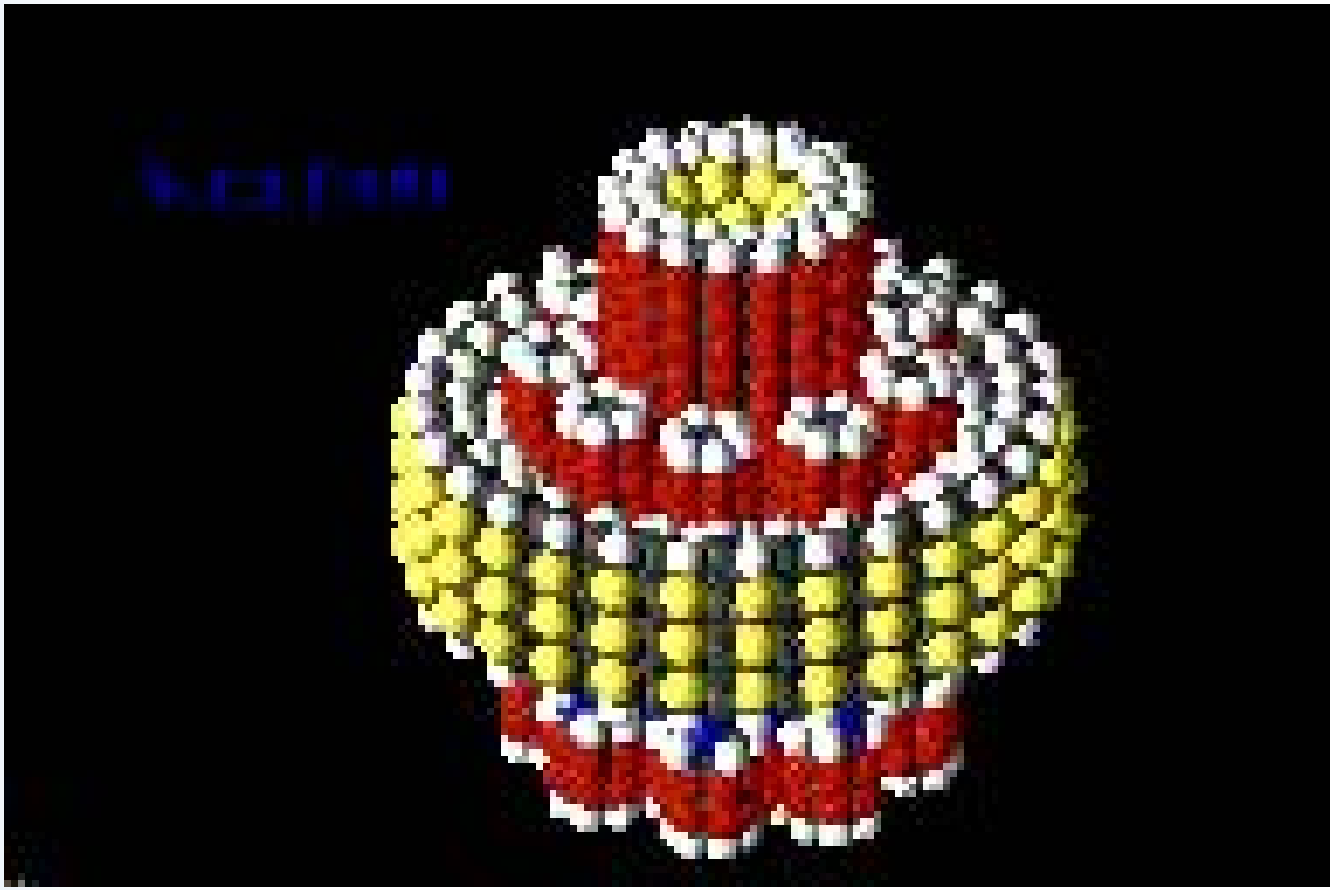


Source: Internet Software Consortium


DECREASE IN TRANSISTOR SIZE
.000001
.00001
.0001
.001
.01
.1
1
10
Molecular Transistor
Silicon Transistor
Diameter (Millimeters)
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
EXPONENTIALSCALE

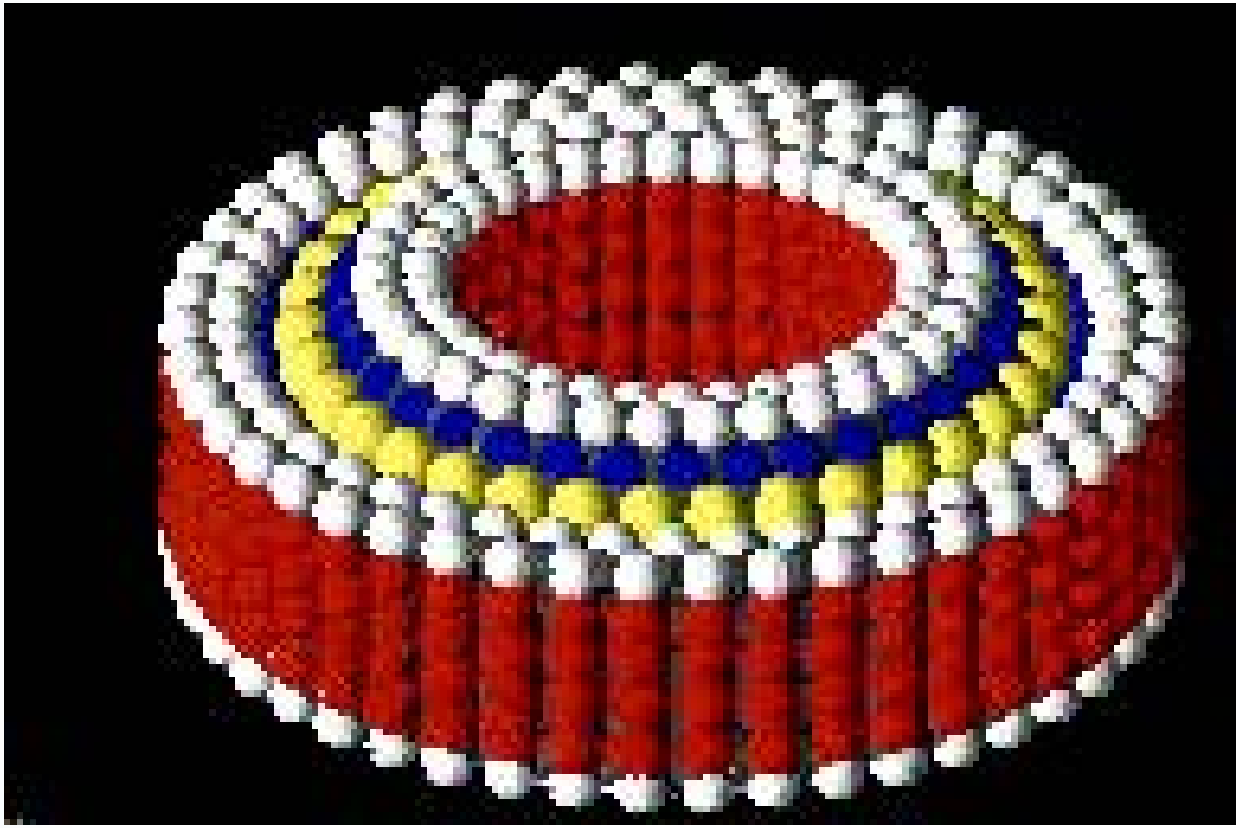

DECREASE IN SIZE OF MECHANICAL DEVICES
.000001
.00001
.0001
.001
.01
.1
1
1965
1971
1976
1982
1987
1993
1998
2004
EXPONENTIALSCALE
Diameter (Millimeter)

Planetary Gear



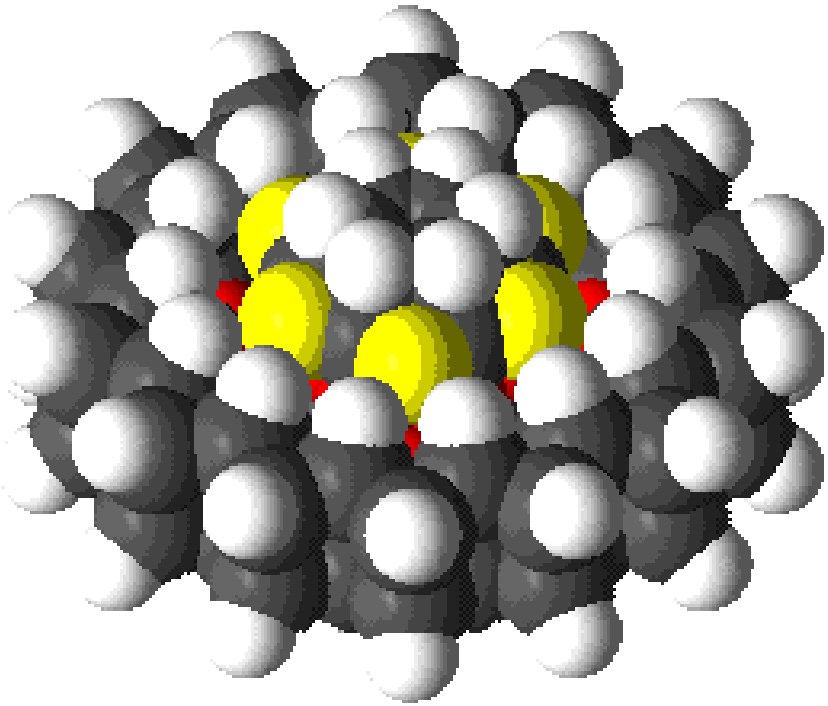
Play Movie

Nanosystems bearing

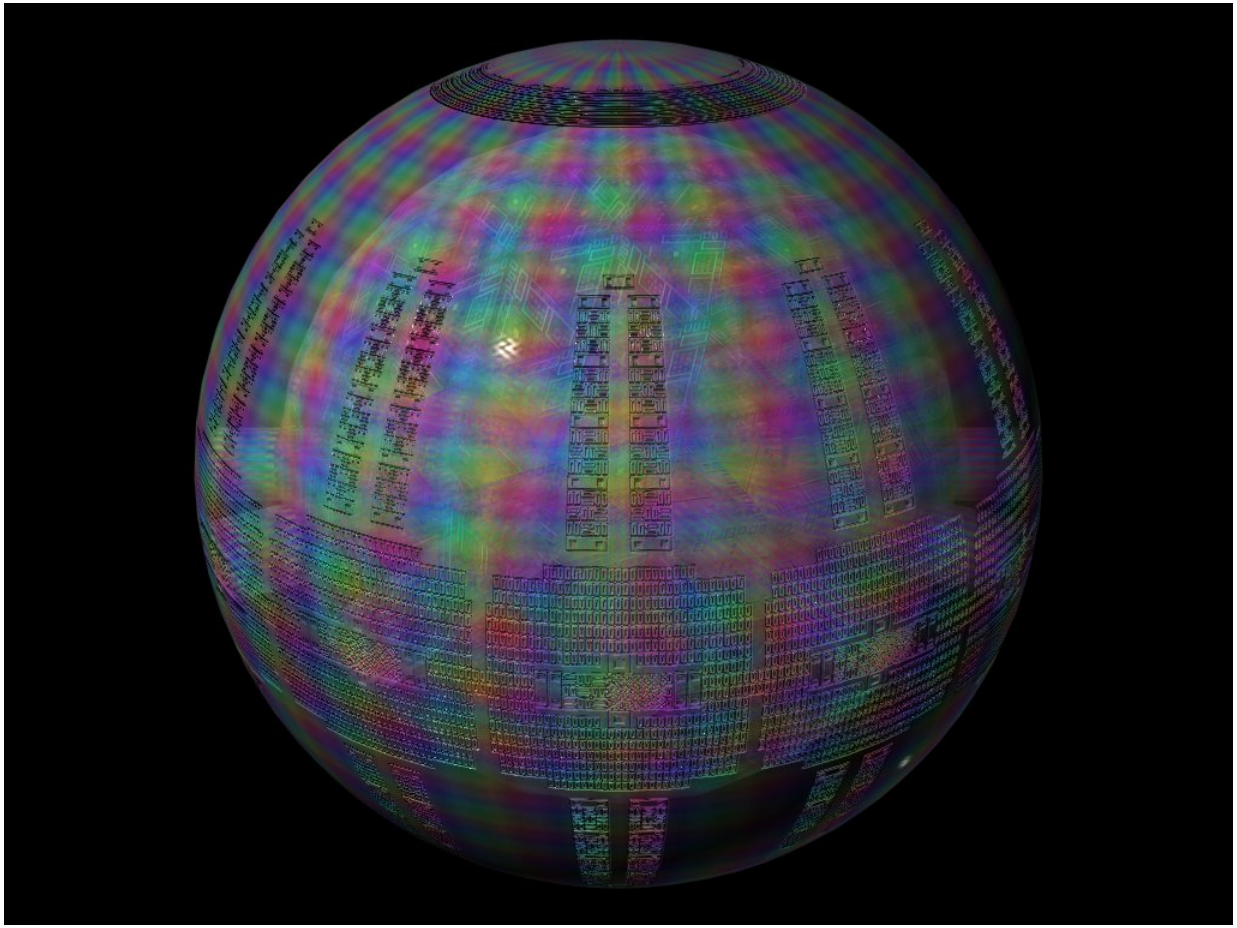


Play Movie

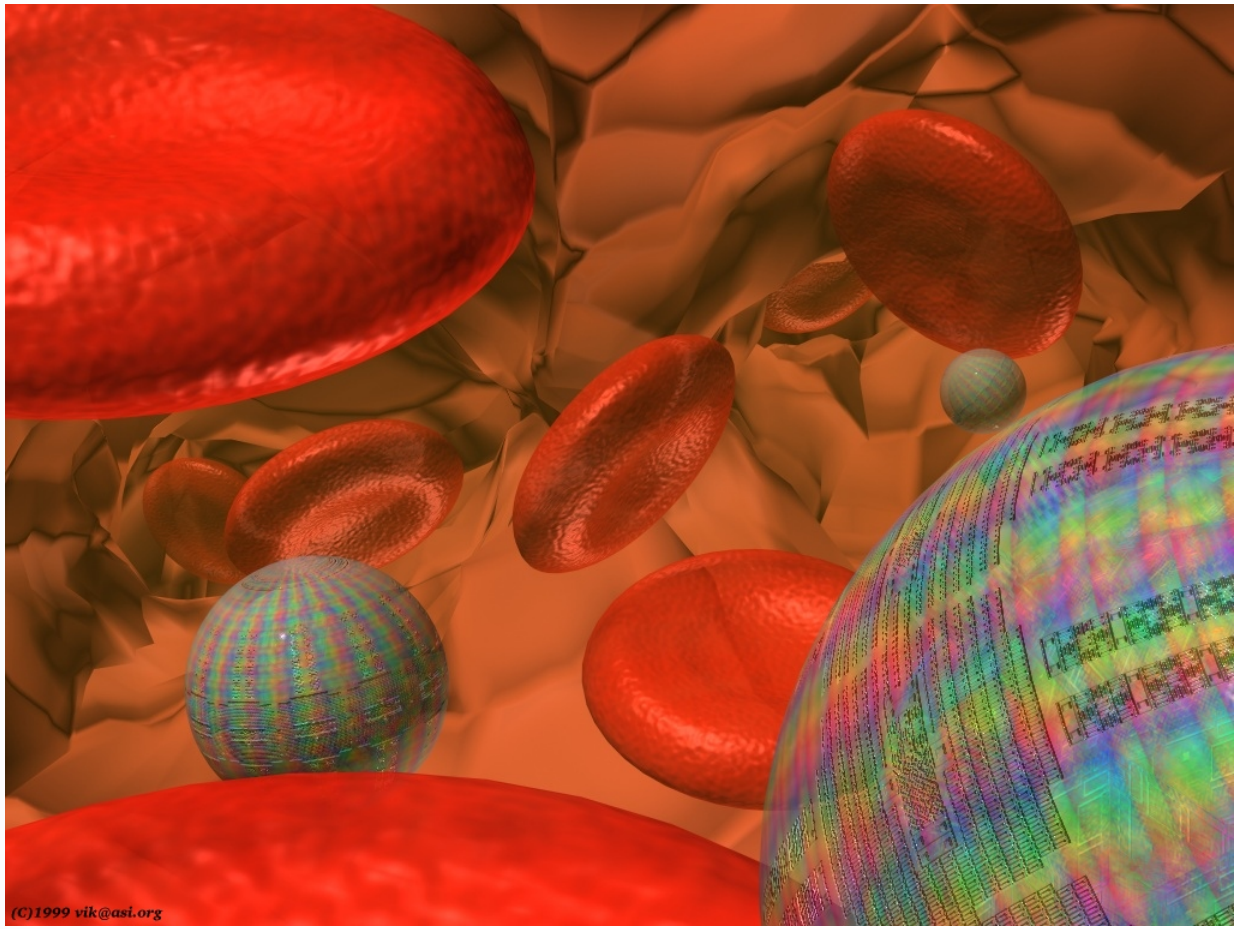
Nanosystems smaller bearing



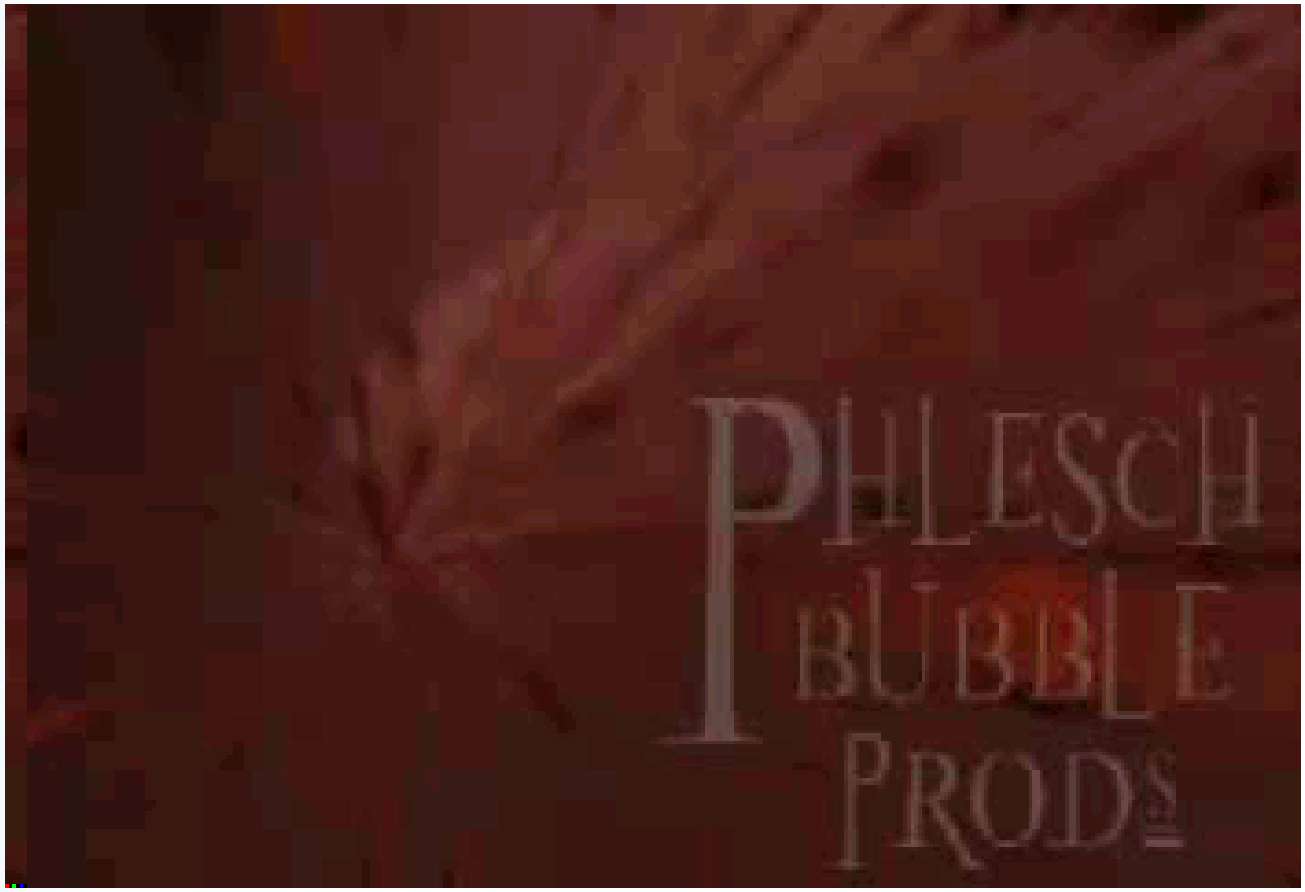
Respirocyte (an artificial red blood cell)



Respirocytes with Red Cells

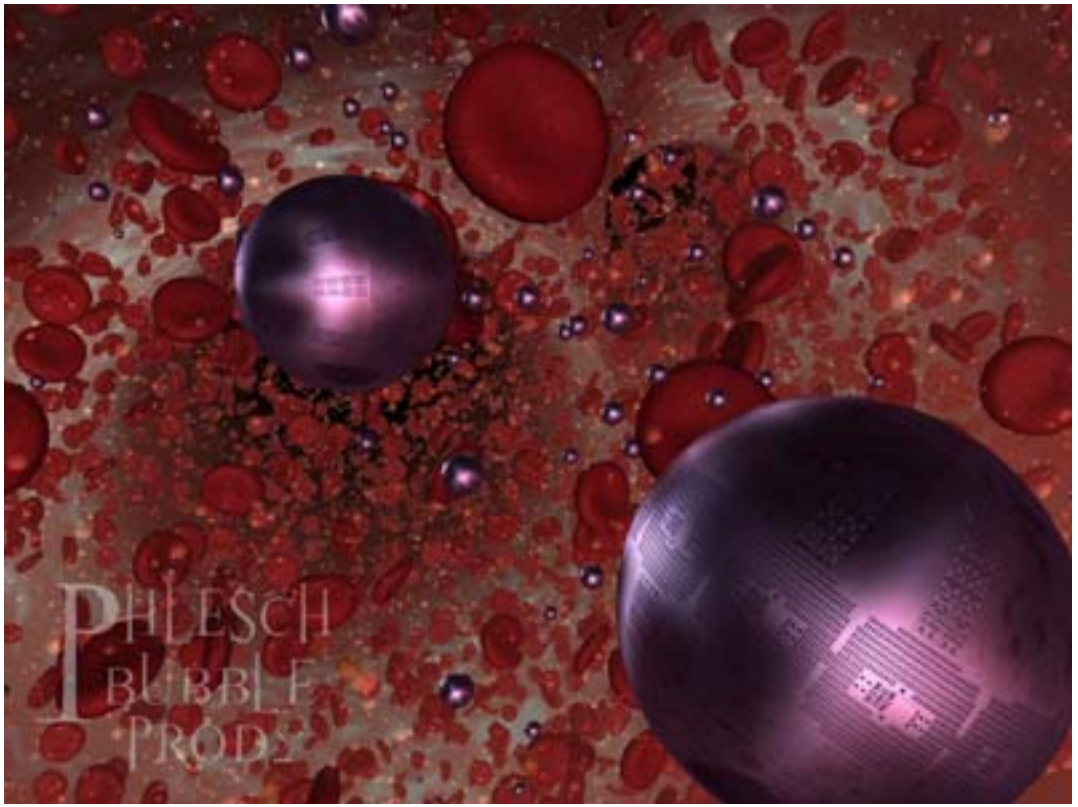


Animation of a respirocyte releasing oxygen in a capillary

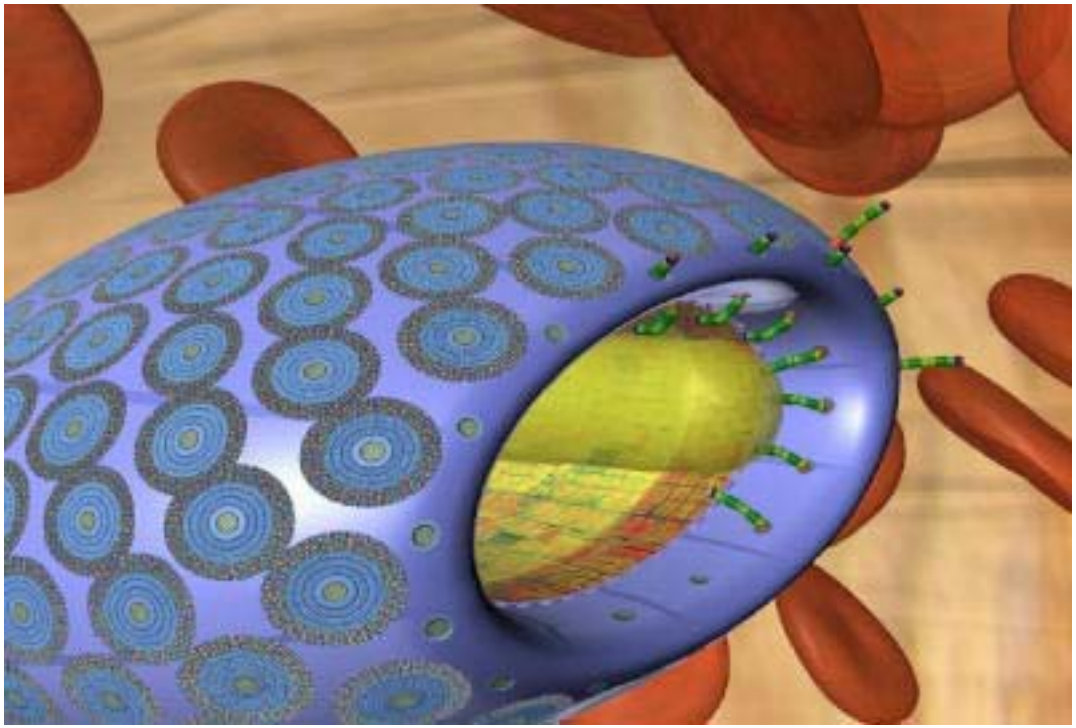


Play Movie

High resolution still from the Animation of a respirocyte

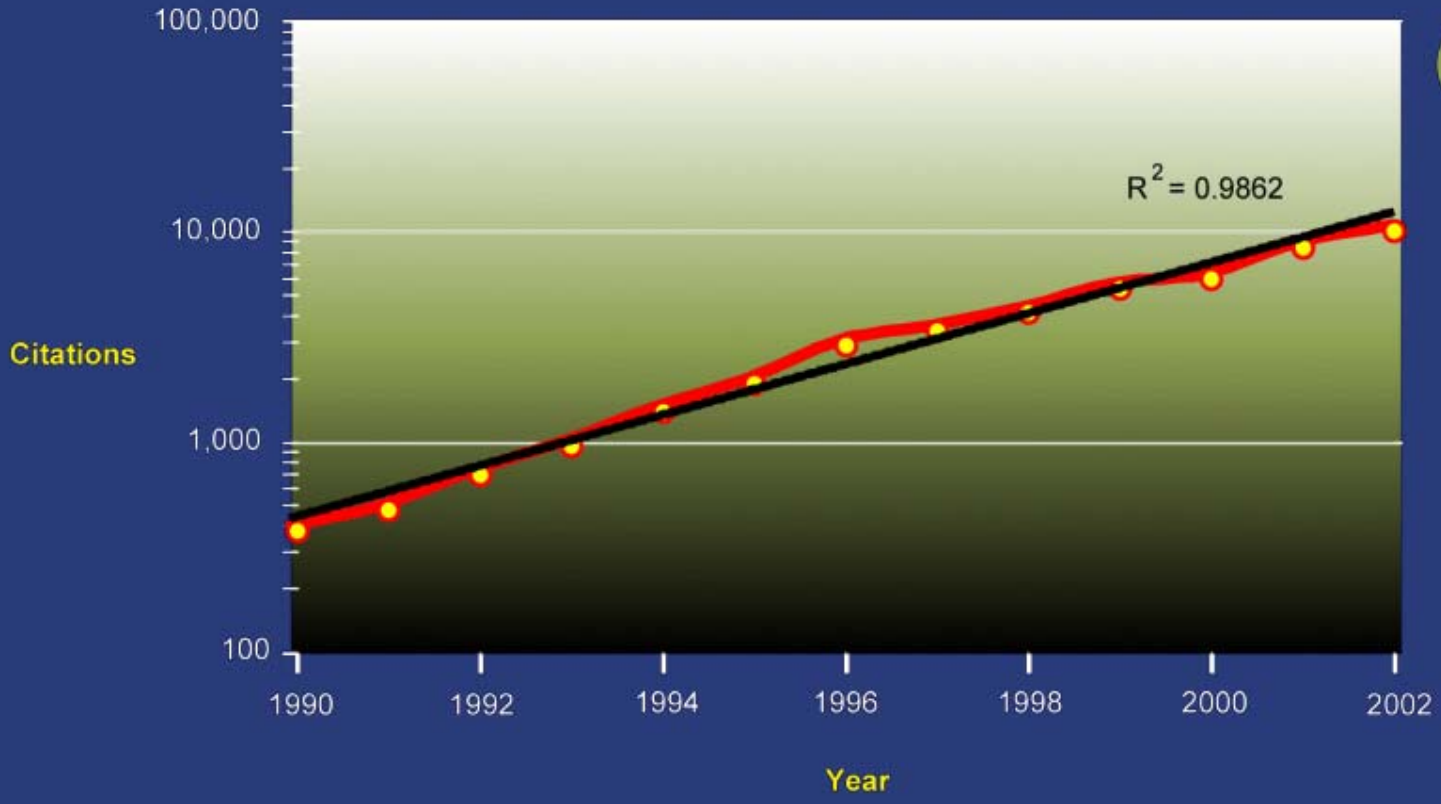


Microbivores II



copyright Zyvex (Katherine Green)

Nanotech Science Citations - 1990-2002

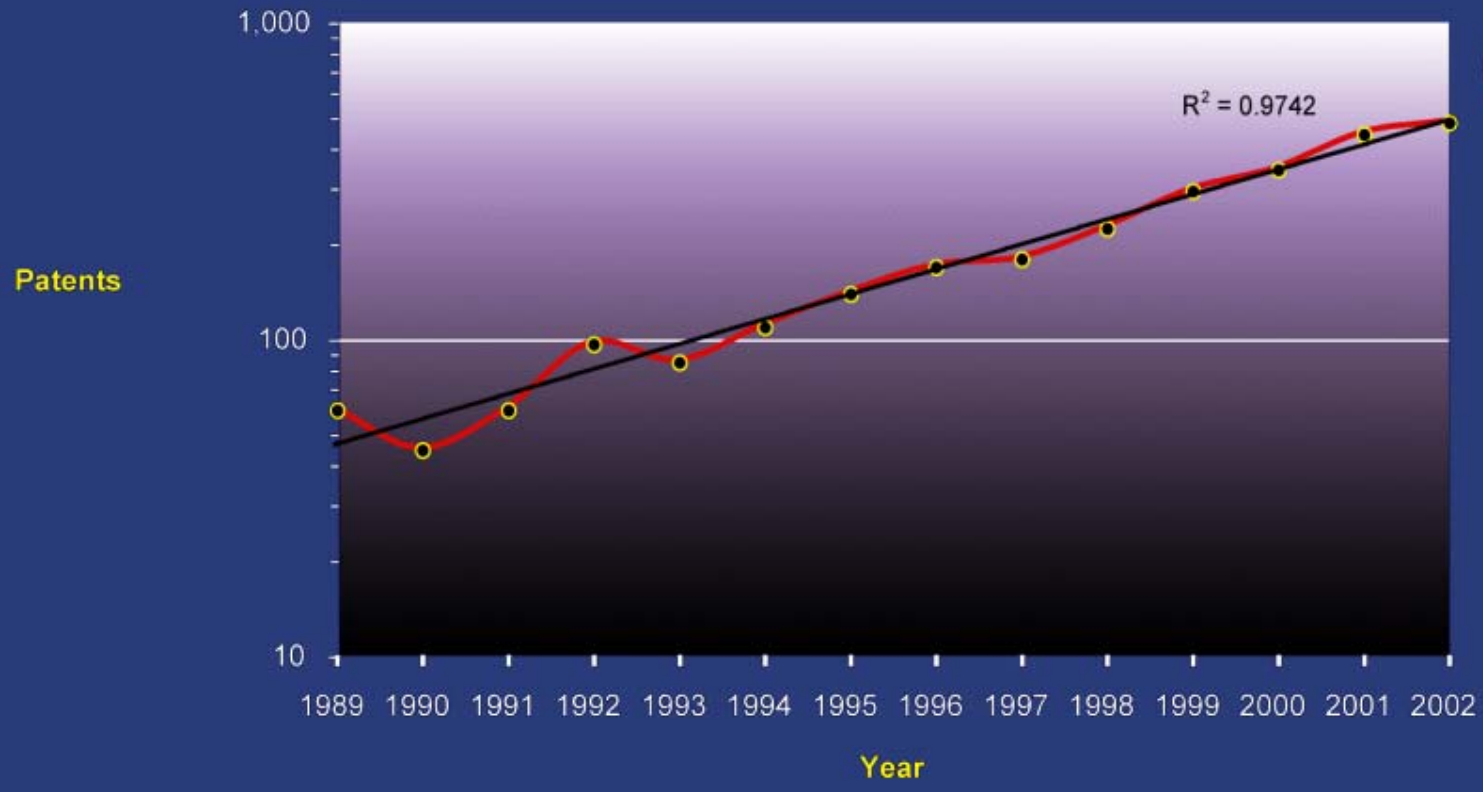


Logarithmic Plot

Source: ETC Group

Doubling time: 2.4 years

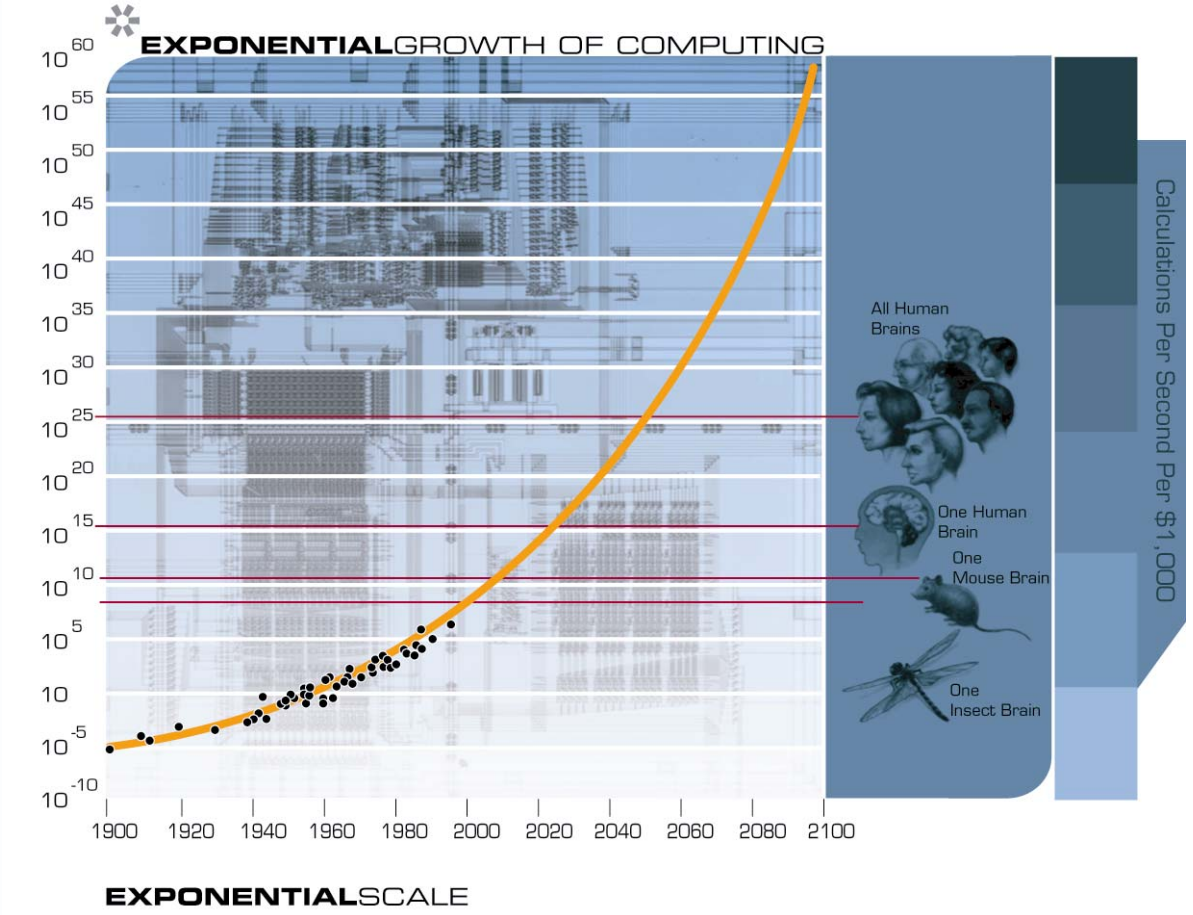
U.S. Nano-Related Patents

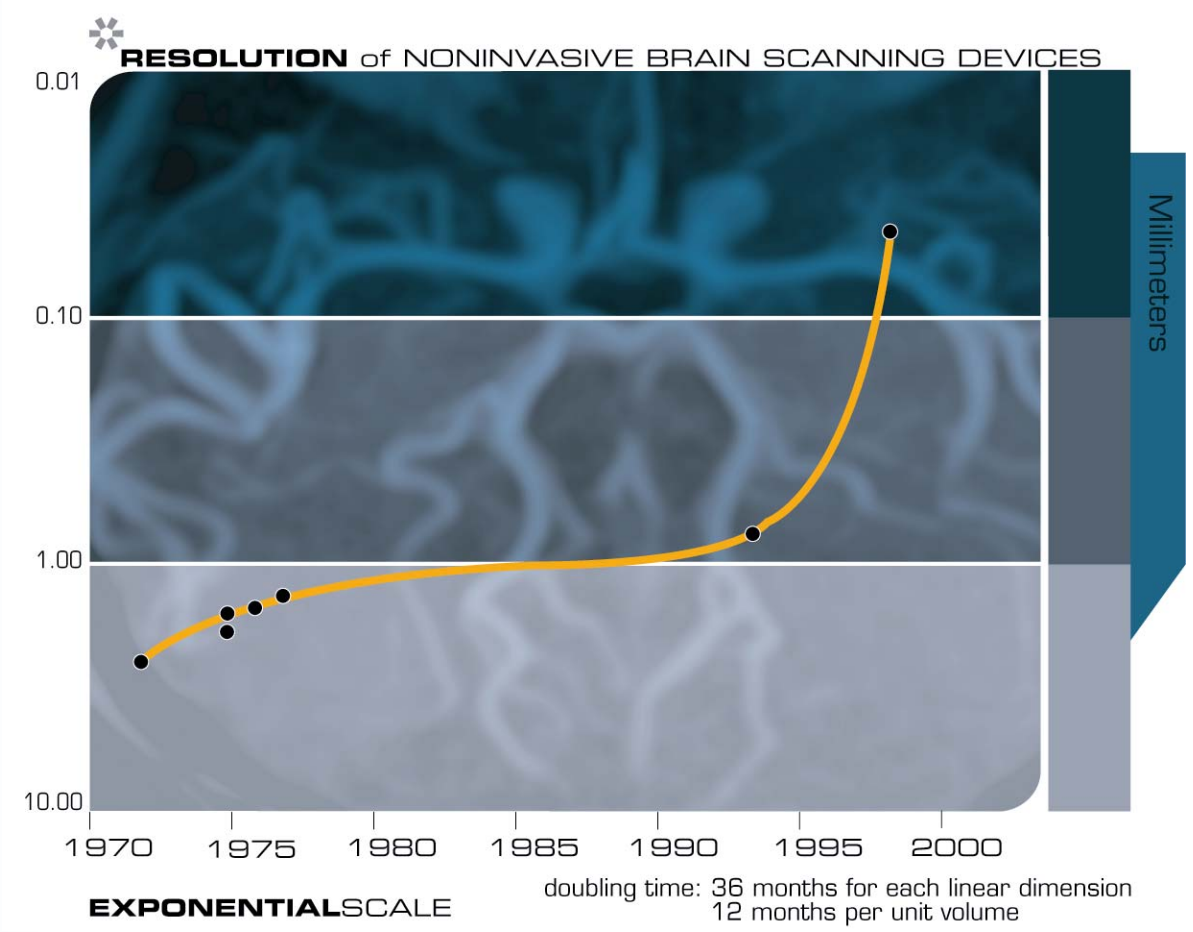


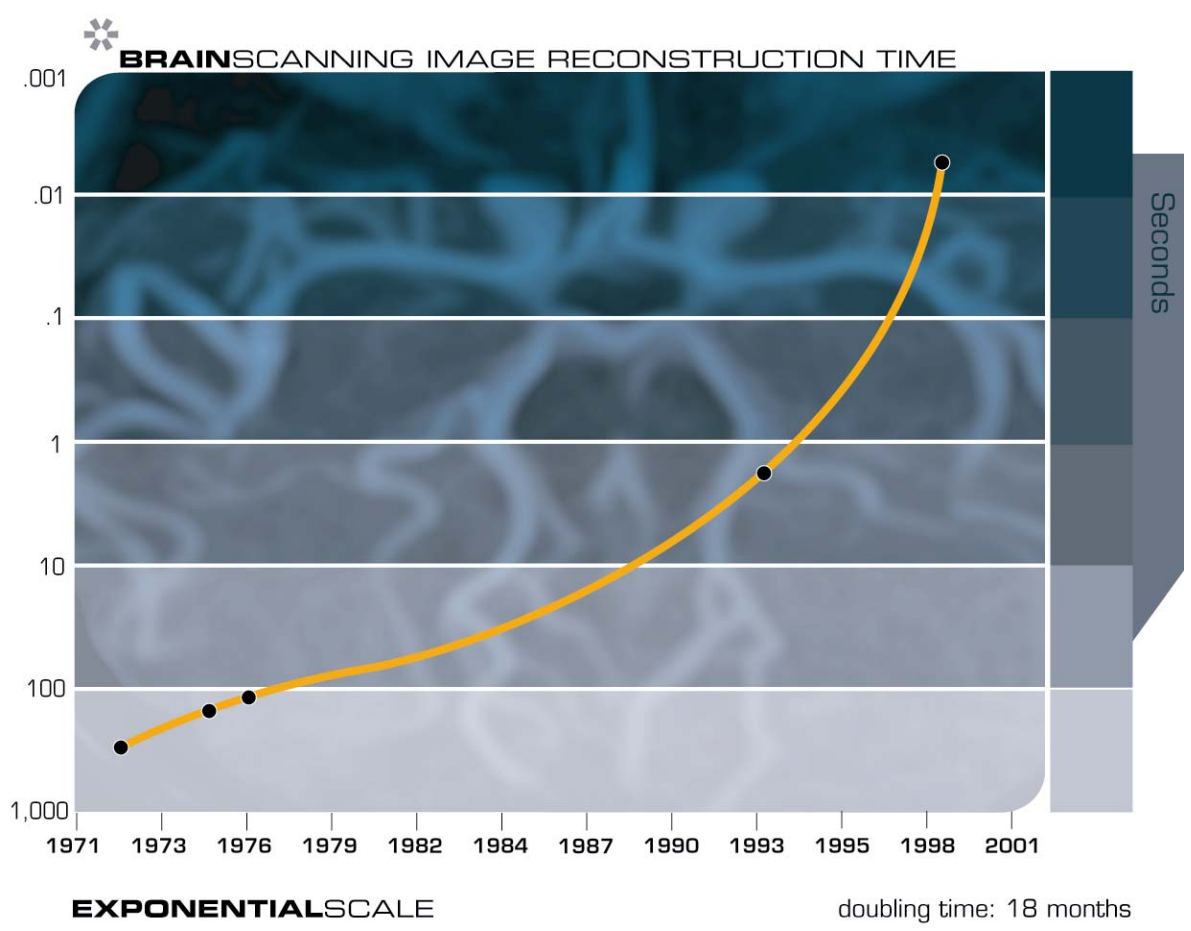
Logarithmic Plot

Source: ETC Group

Doubling time: 4 years


EXPONENTIALGROWTH OF COMPUTING
10^60
10^55
10^50
10^45
10^40
10^35
10^30
10^25
10^20
10^15
10^10
10^5
10
10^-5
10^-10
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
All Human Brains
One Human Brain
One Mouse Brain
One Insect Brain
Calculations Per Second Per $1,000
EXPONENTIALSCALE


RESOLUTION of NONINVASIVE BRAIN SCANNING DEVICES
0.01
0.10
1.00
10.00
Millimeters
1970
1975
1980
1985
1990
1995
2000
EXPONENTIALSCALE
doubling time: 36 months for each linear dimension
12 months per unit volume


BRAINSCANNING IMAGE RECONSTRUCTION TIME
.001
.01
.1
1
10
100
1,000
Seconds
1971
1973
1976
1979
1982
1984
1987
1990
1993
1995
1998
2001
EXPONENTIALSCALE
doubling time: 18 months

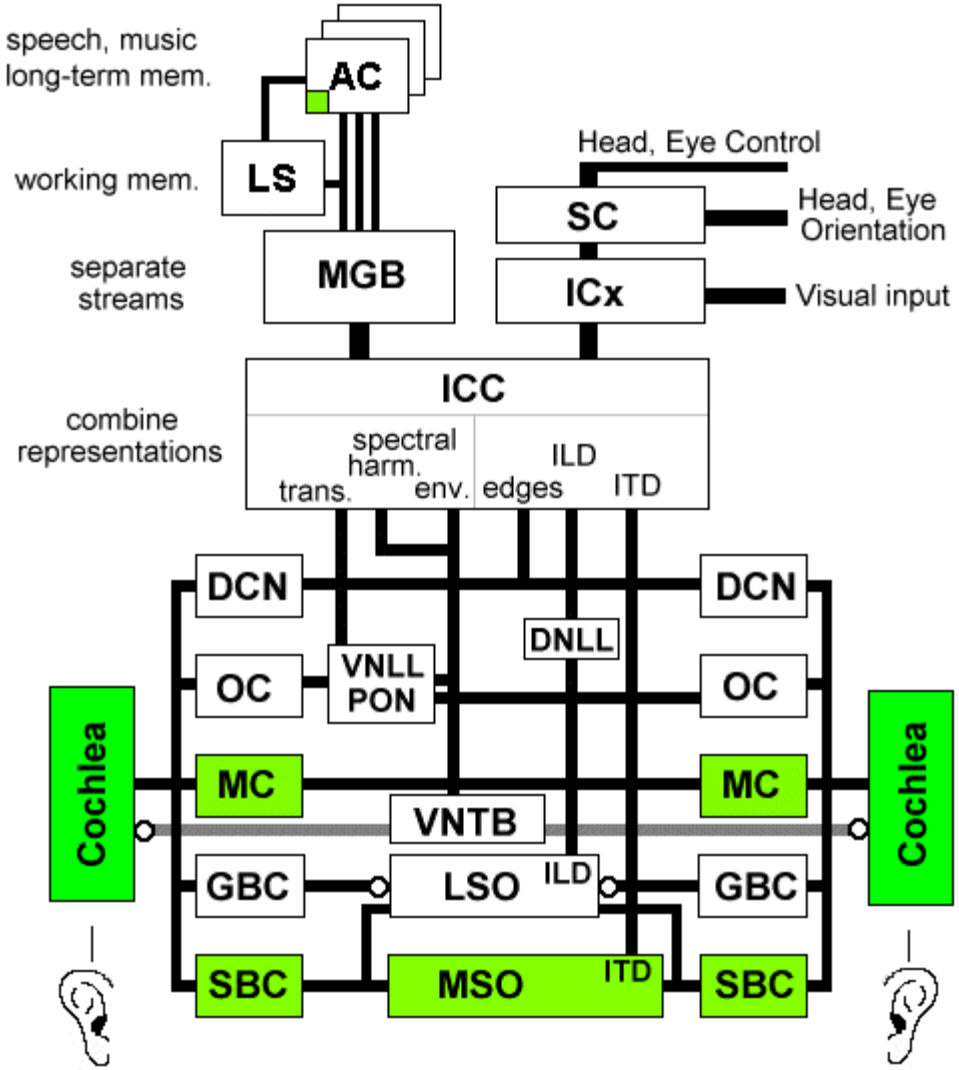
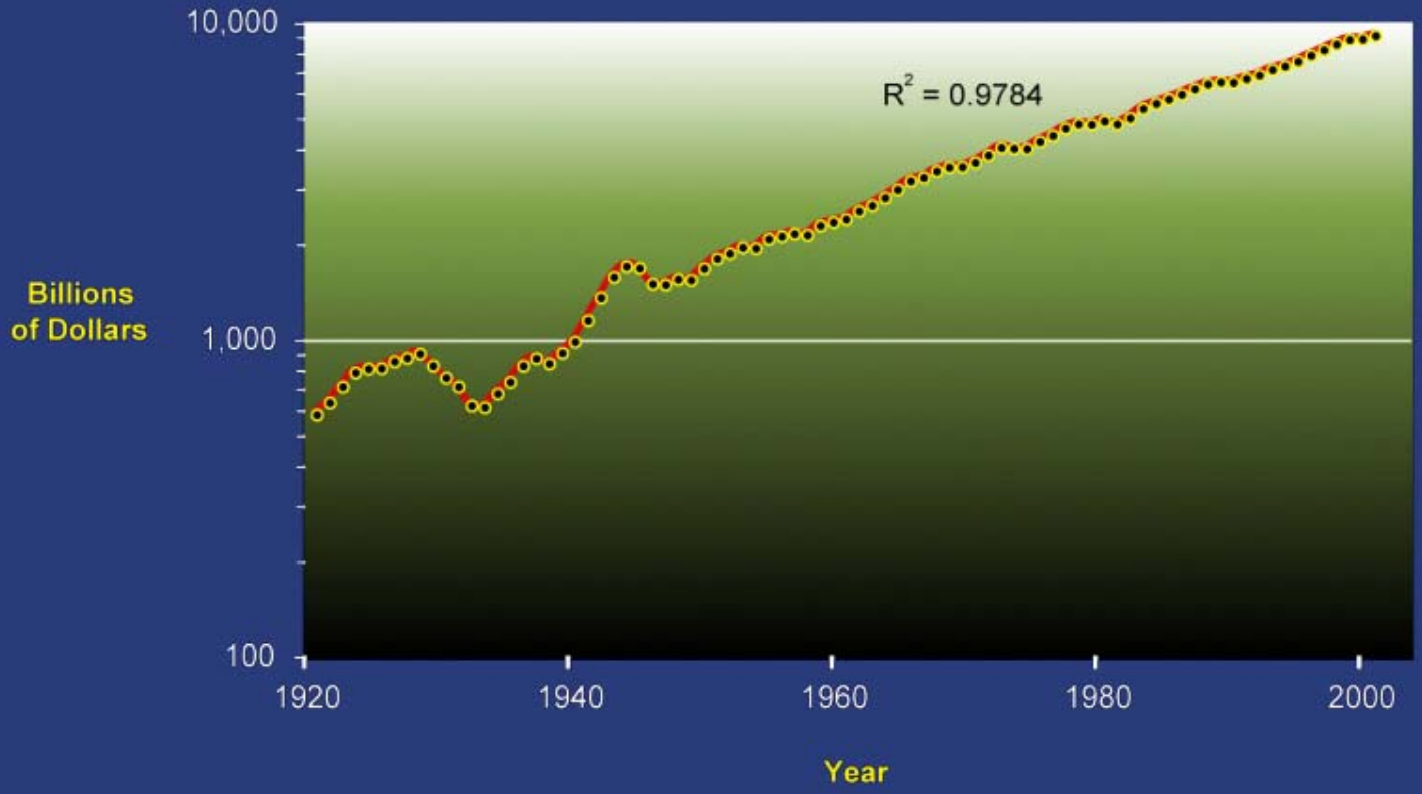


Chart by Lloyd Watts

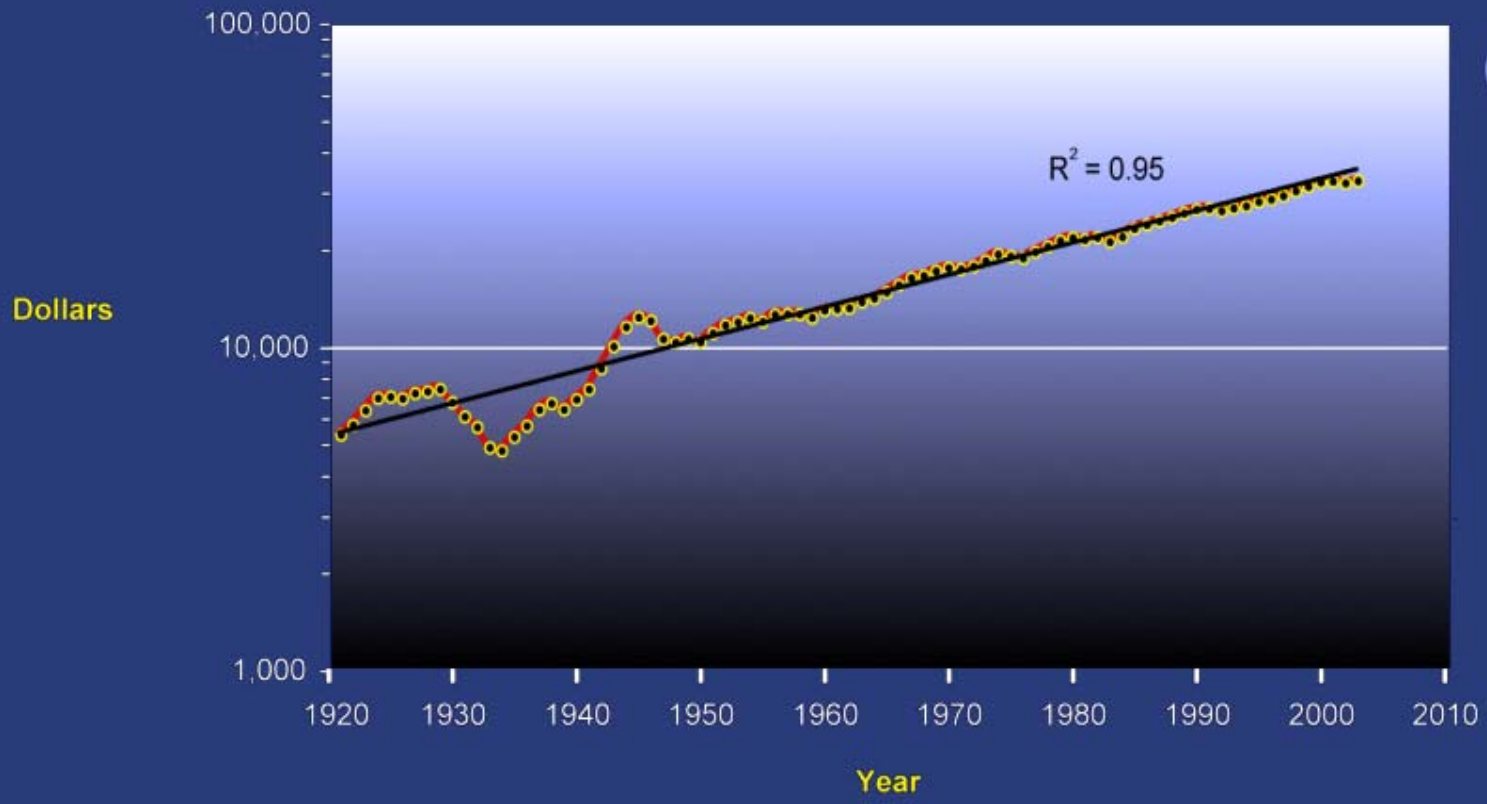
Real Gross Domestic Product



Logarithmic Plot

Source: Bureau of Economic Analysis

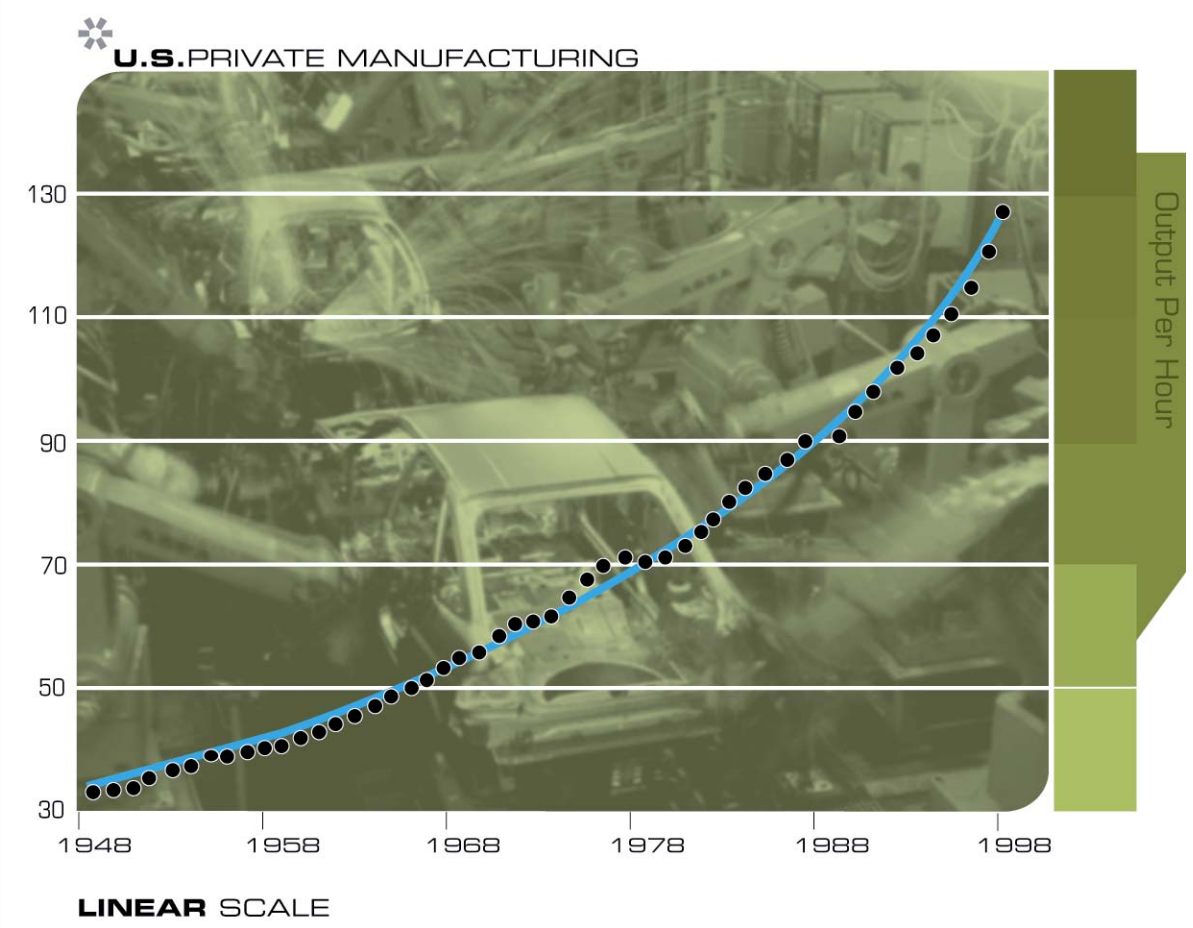
Per Capita GDP



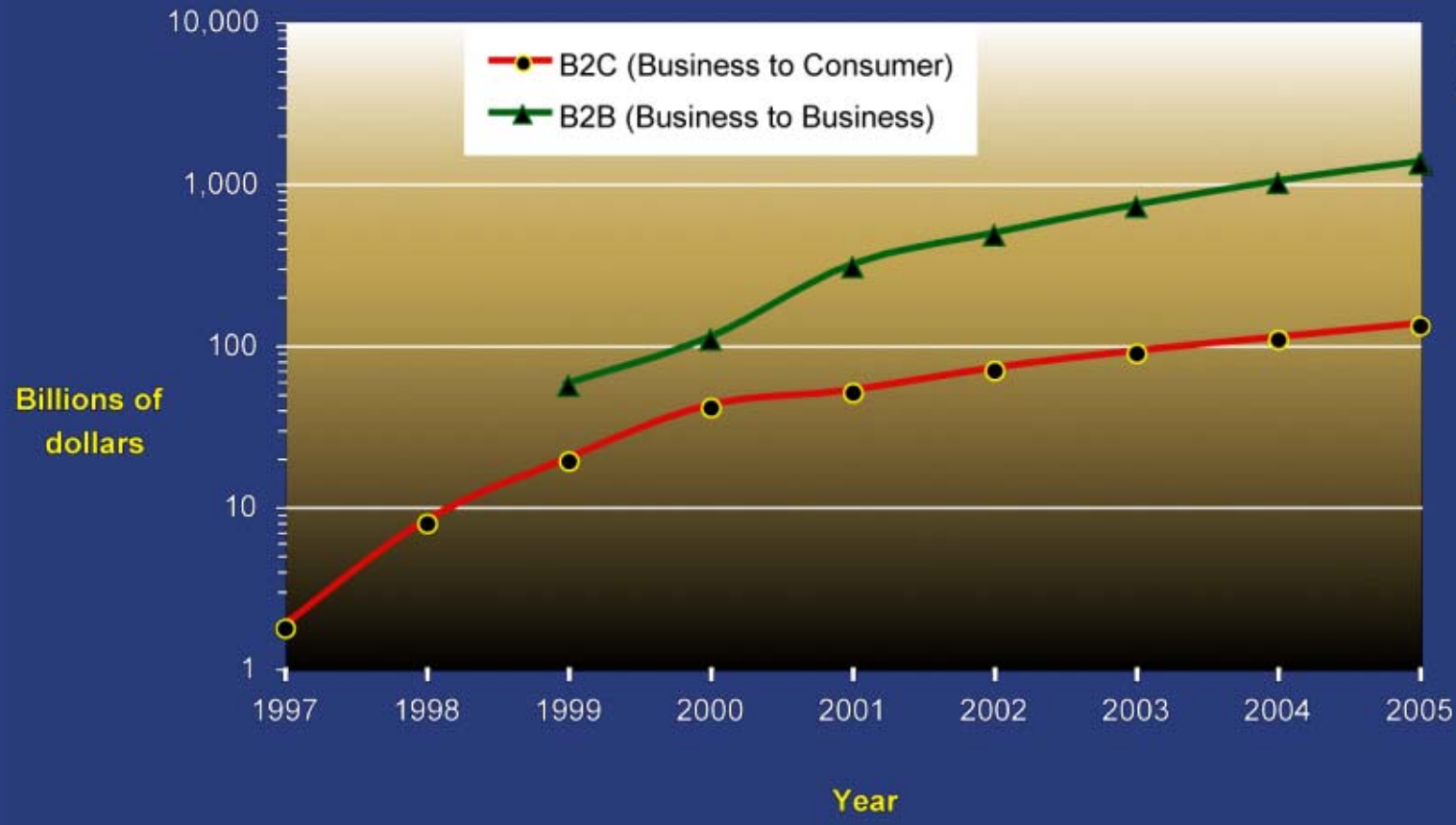
Logarithmic Plot

U.S. Census Bureau

Doubling time: 30 years


U.S. PRIVATE MANUFACTURING
130
110
90
70
50
30
1948
1958
1968
1978
1988
1998
Output Per Hour
LINEAR SCALE

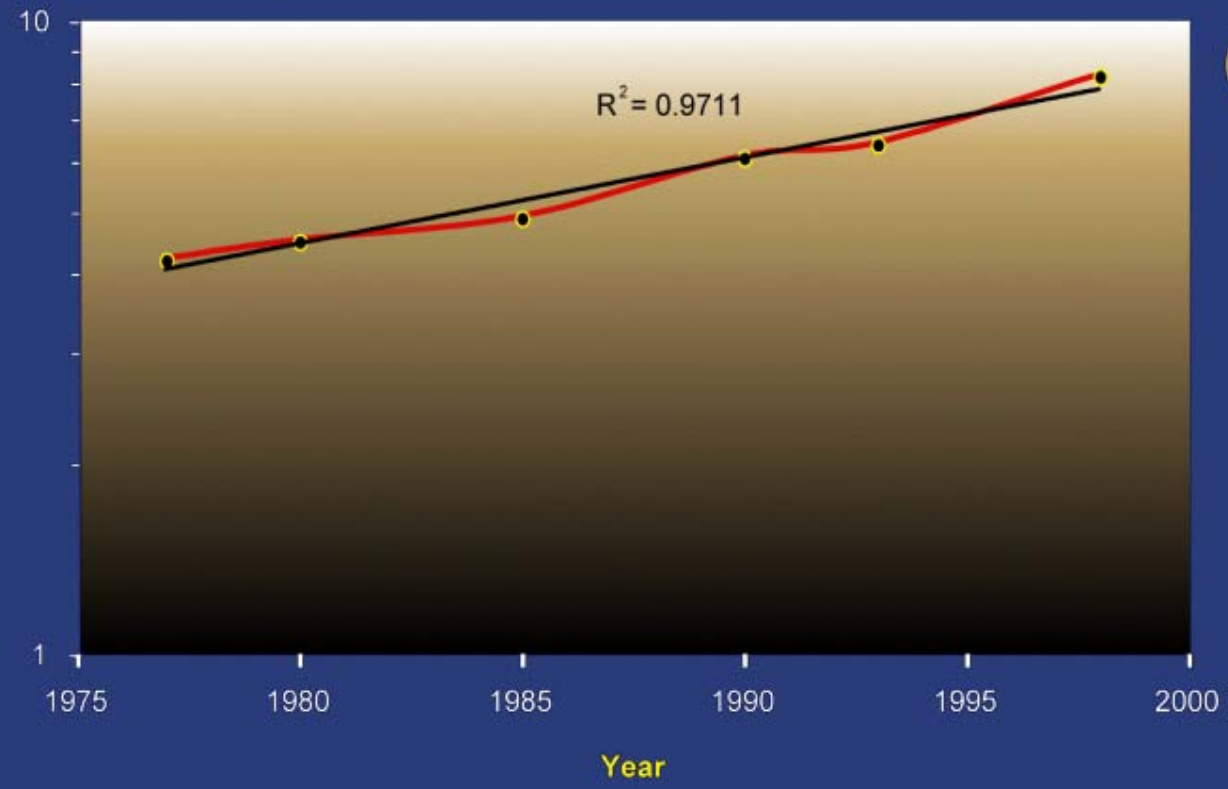
E-Commerce Revenues in U.S.



Logarithmic Plot

Source: eMarketer

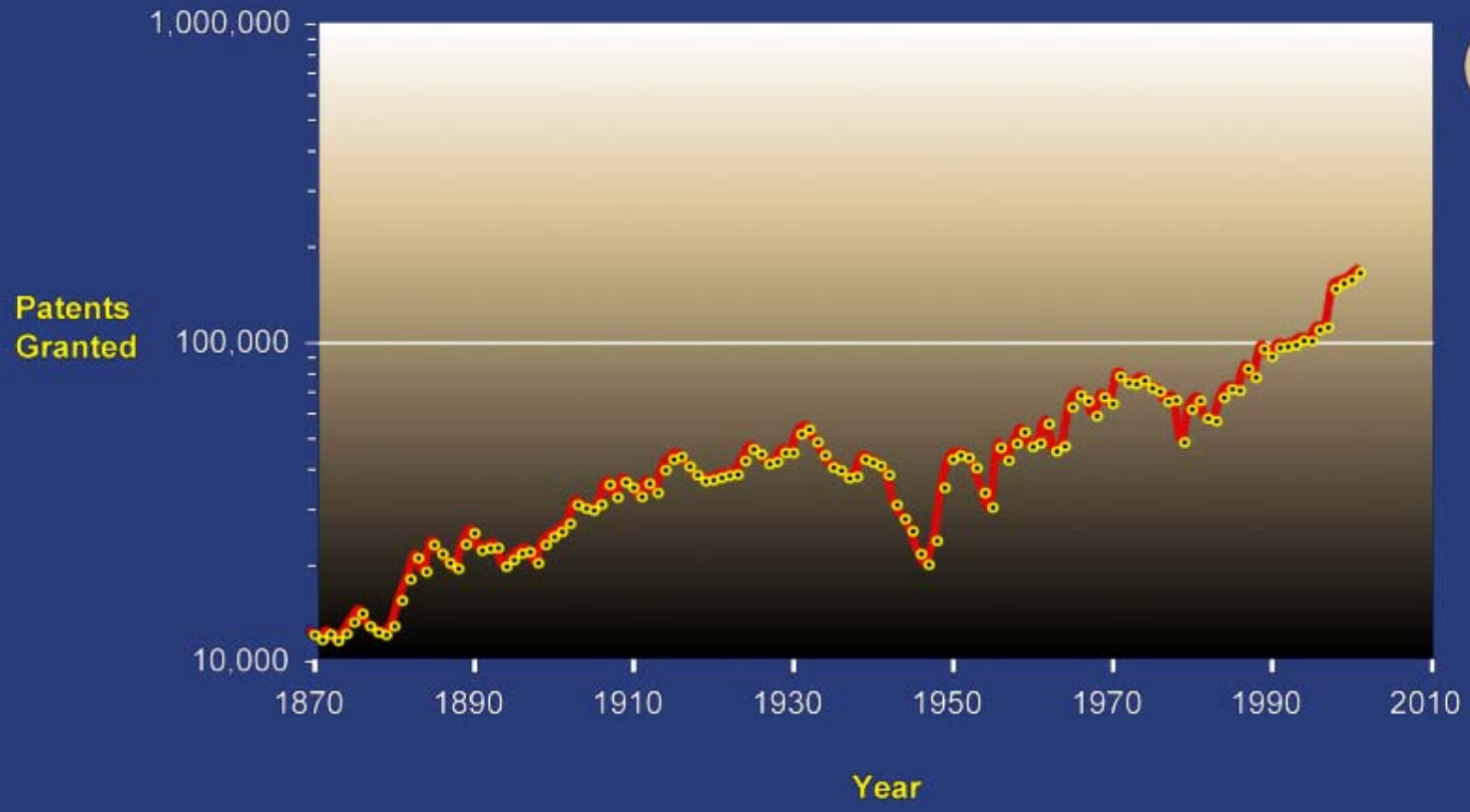
IT's Share of the Economy



Logarithmic Plot

Source: U.S. Department of Commerce

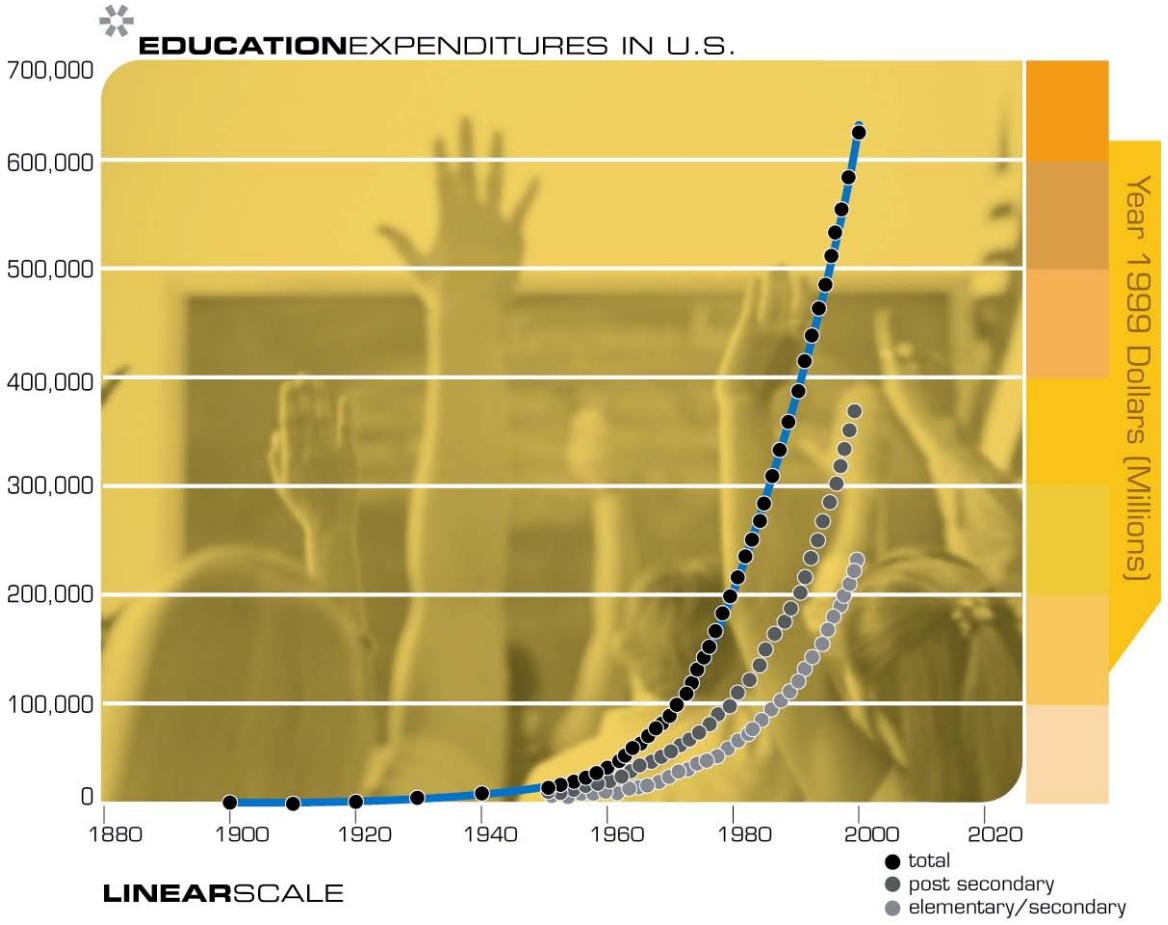
U.S. Patents Granted

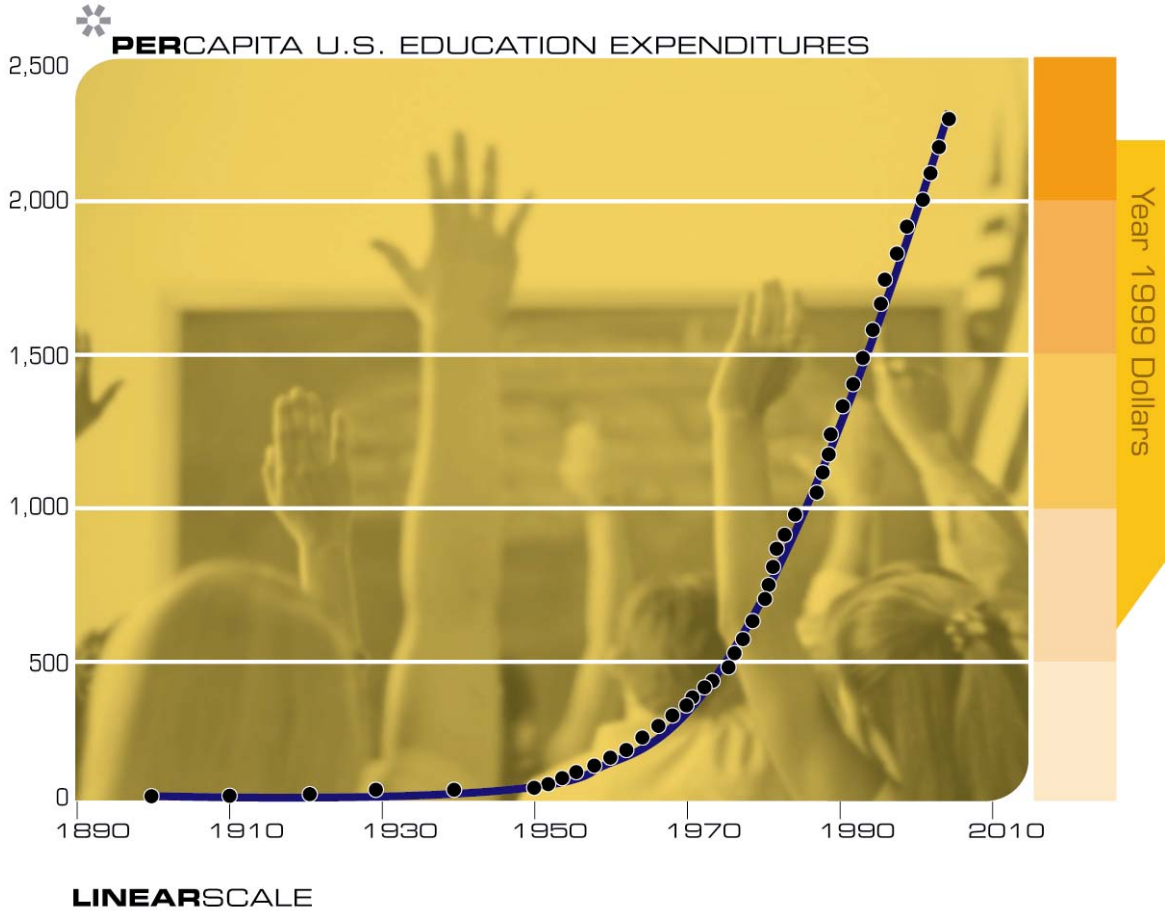


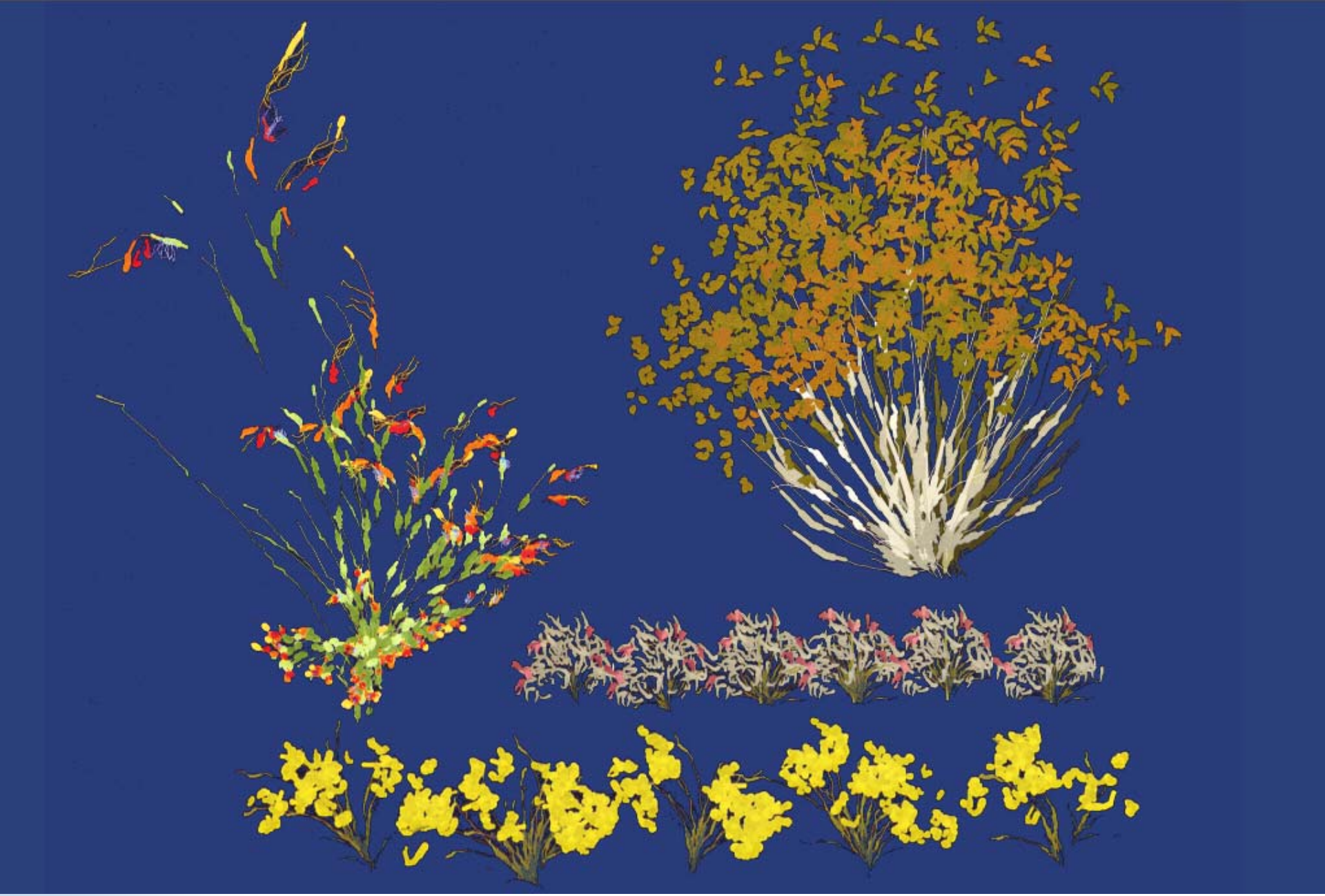
Logarithmic Plot

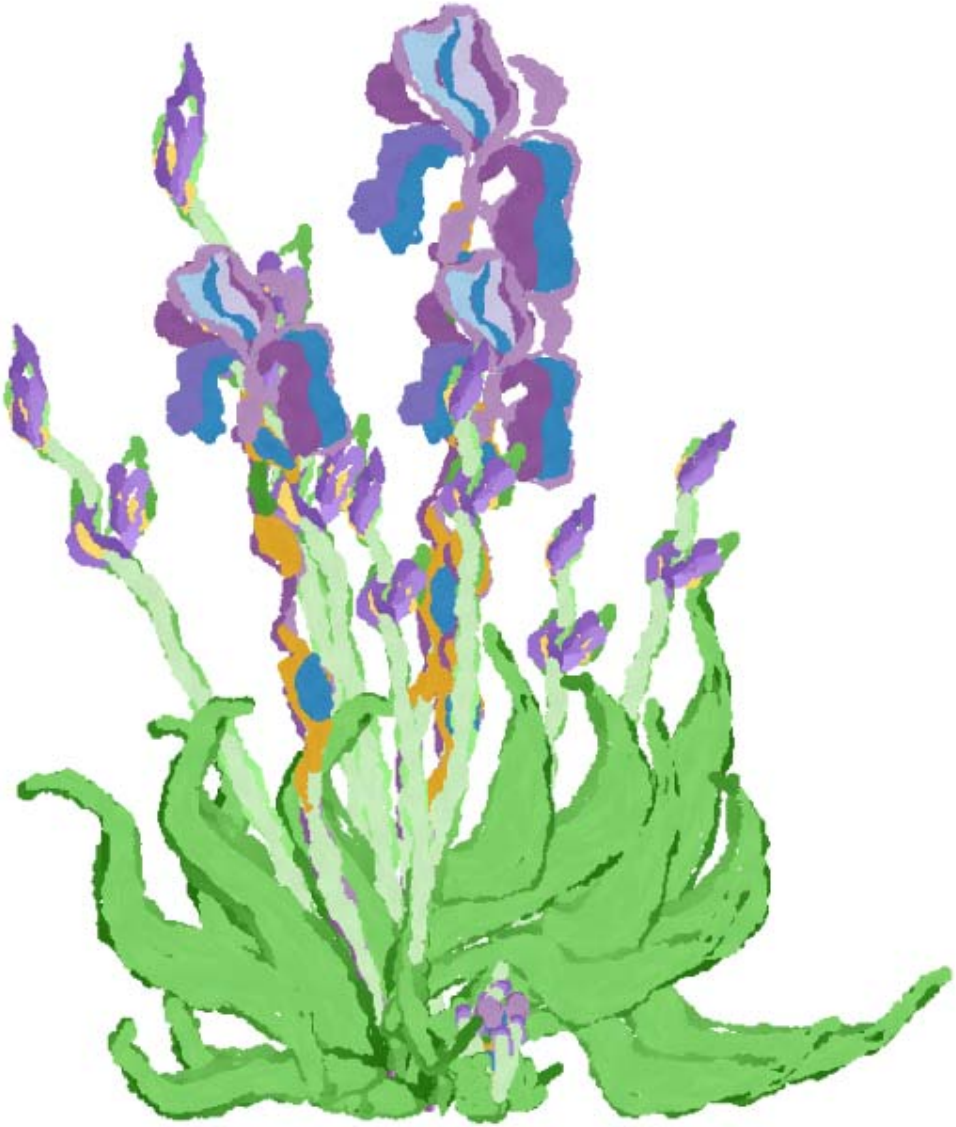
Source: U.S. Patent and Trademark Office

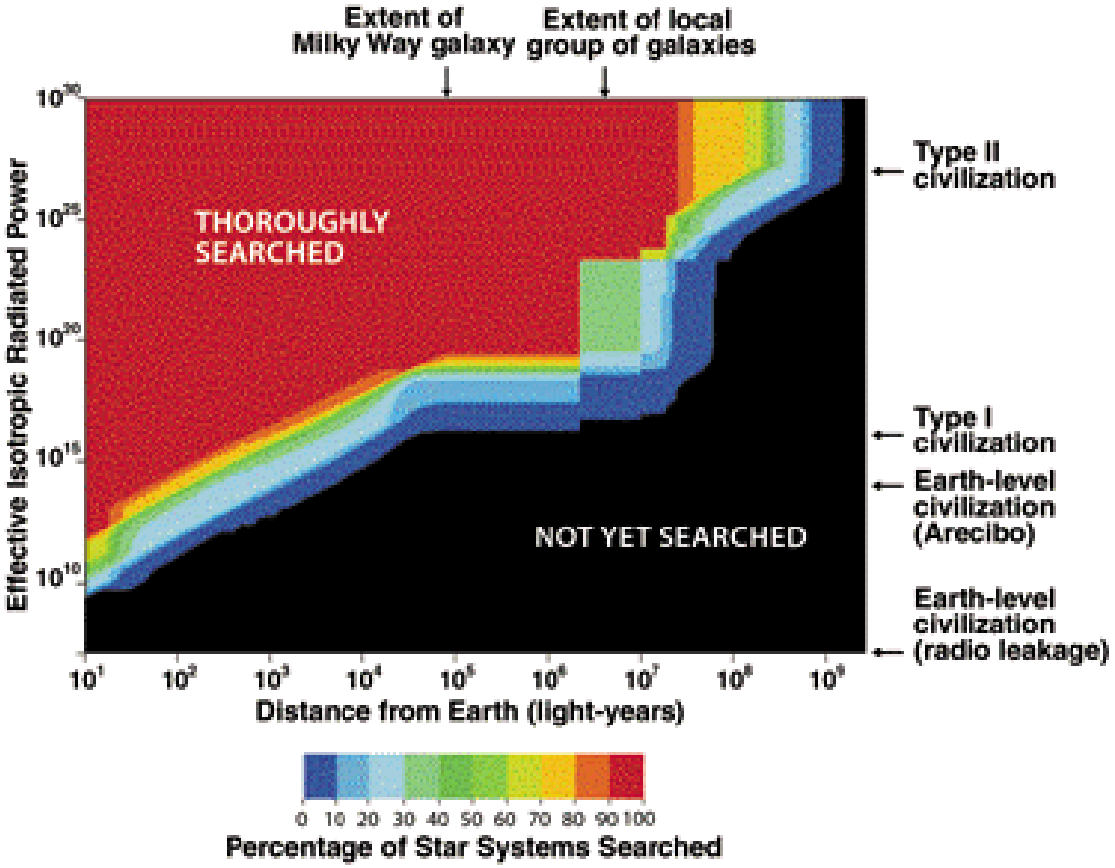
Doubling time: 16 years


EDUCATIONEXPENDITURES IN U.S.
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1880
1900
1920
1940
1960
1980
2000
2020
Year 1999 Dollars (Millions)
LINEARSCALE
total
post secondary
elementary/secondary


PERCAPITA U.S. EDUCATION EXPENDITURES
2,500
2,000
1,500
1,000
500
0
1890
1910
1930
1950
1970
1990
2010
Year 1999 Dollars
LINEARSCALE






Extent of Milky Way galaxy
Extent of local group of galaxies
Effective Isotropic Radiated Power
THOROUGHLY SEARCHED
NOT YET SEARCHED
Type II civilization
Type I civilization
Earth-level civilization (Arecibo)
Earth-level civilization (radio leakage)
Distance from Earth (light-years)
0 10 20 30 40 50 60 70 80 90 100
Percentage of Star Systems Searched

2010: Computers disappear

- Images written directly to our retinas
- Ubiquitous high bandwidth connection to the Internet at all times
- Electronics so tiny it's embedded in the environment, our clothing, our eyeglasses
- Full immersion visual-auditory virtual reality
- Augmented real reality
- Interaction with virtual personalities as a primary interface

Play Movie

2029: An intimate merger

- $1,000 of computation = 1,000 times the human brain
- Reverse engineering of the human brain completed
- Computers pass the Turing test
- Nonbiological intelligence combines
  - the subtlety and pattern recognition strength of human intelligence, with
  - the speed, memory, and knowledge sharing of machine intelligence
- Nonbiological will continue to grow exponentially whereas biological intelligence is effectively fixed

Nanobots provide…

- Neural implants that are:
  - Noninvasive, surgery-free
  - Distributed to millions or billions of points in the brain
- Full-immersion virtual reality incorporating all of the senses
  - You can be someone else
  - “Experience Beamers”
- Expansion of human intelligence
  - Multiply our 100 trillion connections many fold
  - Intimate connection to diverse forms of nonbiological intelligence

The Challenge from Malthus: "Exponential trends eventually run out of resources" However…

- The resources needed for computation and communication are close to zero.
- Based on current understanding, there are sufficient resources on Earth for these trends to continue through the 21st Century:
  - During which time nonbiological intelligence will become trillions of times more powerful than biological human intelligence
  - Beyond that: yet lower thresholds, and expansion beyond Earth

- Specific Paradigms do hit limits
  - e.g., the flat IC's of Moore's Law will hit atomic limits within 15 years
  - But then yield to other paradigms
    - Moore's Law is the fifth paradigm, not the first, to provide exponential growth for computing
    - The Sixth paradigm will be 3D molecular computing
    - The brain achieves its power because it computes in 3 dimensions despite an extremely bulky and slow information processing method (10 million times slower than today's electronic circuits)
  - Even Moore's Law by itself will be sufficient to exceed human intelligence

The Challenge from Software: “We’re making exponential gains in hardware, but not software”

- However, we are making exponential gains in software, although the doubling time is indeed longer.

Software Price-Performance Has Also Improved at an Exponential Rate

Example: Automatic Speech Recognition Software

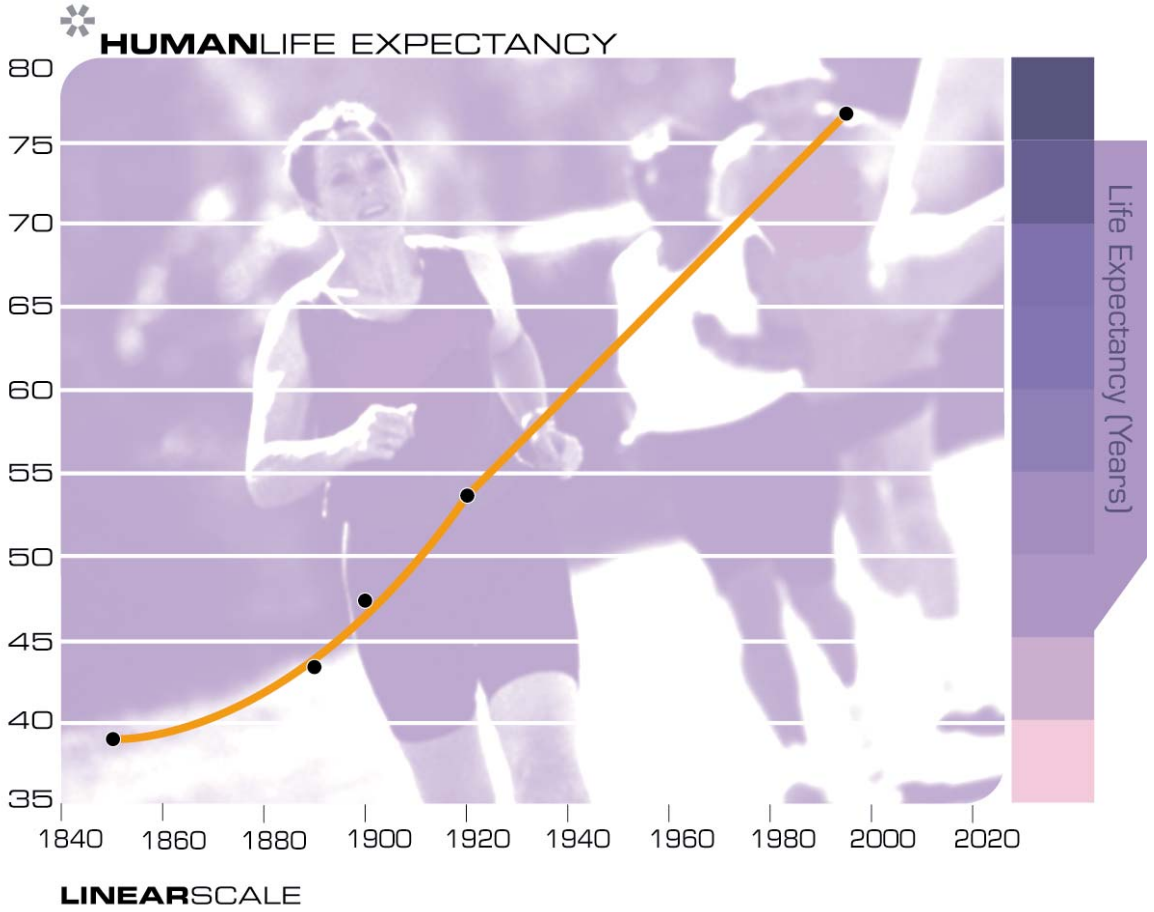
	1985	1995	2000
Price	$5,000	$500	$50
Vocabulary Size (# Words)	1,000	10,000	100,000
Continuous Speech?	No	No	Yes
User Training Required (Minutes)	180	60	5
Accuracy	Poor	Fair	Good

- There has been increased productivity from new languages, class libraries, software development tools:
  - Doubling time is about 6 years
- Software complexity required to emulate the human brain is manageable:
  - Compressed genome data that describes the human brain is 12 million bytes
    - 6 billion bits X compression factor of 30 X 50% devoted to the brain

- We have a specific game plan to reverse engineer the human brain
  - Knowledge of the human brain at all levels is growing exponentially
- We will not program human-level intelligence link by link (e.g., the expert system “cyc”)
  - But rather as an elaborate architecture of parallel self-organizing systems
  - Educating such a system will be the hardest part of the software task

The Challenge from Ethics

- There is far less ethical resistance to the development of nonbiological intelligence (including intimate connection with our bodies and brains) than to biological tinkering
- In any event, ethical concerns end up as stones in a stream: the economic and moral imperatives are too strong
- There ultimately will be grave dangers, but the biological downsides are more apparent today


HUMANLIFE EXPECTANCY
80
75
70
65
60
55
50
45
40
35
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
LINEARSCALE
Life Expectancy (Years)

Graphs available at:

KurzweilAI.net

"The Law of Accelerating Returns"

Reference URLs:

Kurzweil Technologies (links to all Kurzweil companies)

www.KurzweilTech.com

AARON and Cybernetic Poet:
www.KurzweilCyberArt.com

KAIN: **www.KurzweilAI.net**